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Department of
Agriculture

Forest Service

Forest Pest
Management

Davis, CA

C-47 AIRCRAFT SPRAY DEPOSITION

PART 1: A STATISTICAL INTERPRETATION

FPM 94-11
May 1994

Pesticides used improperly can be injurious to human beings, animals, and plants. Follow the directions and heed all precautions on labels. Store pesticides in original containers under lock and key—out of the reach of children and animals—and away from food and feed.

Apply pesticides so that they do not endanger humans, livestock, crops, beneficial insects, fish, and wildlife. Do not apply pesticides where there is danger of drift when honey bees or other pollinating insects are visiting plants, or in ways that may contaminate water or leave illegal residues.

Avoid prolonged inhalation of pesticide sprays or dusts; wear protective clothing and equipment, if specified on the label.

If your hands become contaminated with a pesticide, do not eat or drink until you have washed. In case a pesticide is swallowed or gets in the eyes, follow the first aid treatment given on the label, and get prompt medical attention. If a pesticide is spilled on your skin or clothing, remove clothing immediately and wash skin thoroughly.

NOTE: Some States have restrictions on the use of certain pesticides. Check your State and local regulations. Also, because registrations of pesticides are under constant review by the U.S Environmental Protection Agency, consult your local forest pathologist, county agriculture agent, or State extension specialist to be sure the intended use is still registered.

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C-47 AIRCRAFT SPRAY DEPOSITION

PART 1:

A STATISTICAL INTERPRETATION

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Summary

An aerial spray field test conducted by the USDA Forest Service in cooperation with the US Army Deseret Test Center in 1972 provides three sets of multiple-spray deposit card line data with which to perform statistical analysis on the deposition data collected. The test was conducted over flat, open desert terrain of western Utah. Common practice for most field testing is to use three or fewer card lines to characterize ground deposition. It is shown, through accepted statistical techniques, that a level of confidence in the field test results can be established if three or more card lines are used, or if multiple sampling stations are used at selected points parallel to the flight path. Several suggestions are made to improve the recovery of accurate field data, and improve the quality of the results.

Table of Contents

1. Introduction

In the spring of 1972, the USDA Forest Service (FS) and U.S. Army Deseret Test Center conducted a cooperative test to obtain aerial spray data on the U.S. Air Force (USAF) PWU-5/A Modular Internal Spray System (MISS). This system was developed in response to USAF Special Operations Force requirements, which include the capability for aerial application of pesticides for insect and vegetation control. The test is described in detail by Taylor et al. (1972). The MISS was installed on a C-47 aircraft and tested with a formulation of the insecticide Zectran®. In order to evaluate system effectiveness, and to satisfy licensing requirements for the Zectran® formulation, a FS spray system installed on a C-47 was included in the test as a baseline system. The C-47 is the military version of the DC-3.

The test consisted of seven trials, six at the US Army Dugway Proving Ground (DPG) in Utah and one at Lolo National Forest in Montana. The DPG trials evaluated the FS spray system and the MISS spray system over open and flat desert terrain; three trials were conducted using the baseline FS system and three trials were conducted using the MISS. The trial at Lolo National Forest was an operational demonstration of the MISS over forested terrain.

The first three trials conducted at DPG (all using the baseline FS spray system) were well documented and were conducted over a 1/2 mile x 1/2 mile horizontal grid. Thus, ground deposition data from these trials can be organized into many lines of deposition (or sample card lines) normal to the aircraft flight path, and a mean deposition profile for each trial can be calculated. Trials FS1, FS2 and FS3 generated data over large portions of the grid: deposition from FS1 and FS2 can be represented by 25 card lines and FS3 by 16 card lines.

The large number of card lines for each of the three trials permit us to test the FS practice of single or multiple card lines to recover an accurate representation of deposition. It has been shown that estimates of the actual mean deposition become more precise as the number of independent samples of the deposition (i.e., the number of card lines used in testing) is increased (Teske 1992). This report will further examine the effect of the number of card lines used to generate the mean deposition profile, and draw conclusions based on these results.

This report and a companion report which describes FSCBG model prediction of this test (MacNichol and Teske, 1994b) are the first detailed analyses of the 1972 MISS test in the 22 years since it was conducted. The test is unique for several reasons: never has there been another opportunity to fly an aircraft over such a densely sampled grid array to look at the "footprint" of a spray pattern; never have there been so many samples; and, this aerial spray field test is the only test ever conducted in which live insects were placed on the grid with deposition samples in order to look at the dose/response. The first and last aspects of the field test form the subject of the report by MacNichol and Teske (1994b); the present report examines the statistics of the multiple card line samples. Now that there is a reliable predictive model for aerial spray field tests (the Forest Service Cramer-Barry-Grim FSCBG model 4.3, Teske et al. 1993), the abundance of deposition data available from the 1972 MISS test makes it an ideal candidate for the ongoing FSCBG validation study (MacNichol and Teske 1993a, 1993b, 1994a).

2. Field Trials Summary

2.1 Test Scope

The MISS test consisted of seven trials, six conducted at DPG, Utah and one in the Lolo National Forest, Montana. Four test phases, designated A through D, were conducted from late April through late June 1972. Table 1 summarizes the location, date and requirements for each test phase.

This report will use data generated during phase A (trials FS1, FS2 and FS3), since meteorological data for phases B, C, and D are incomplete. Phase A was conducted at DPG with the FS spray system on a C-47 aircraft. All three trials in this phase took place on April 27, 1972.

2.2 Spray Site

The trials of interest were conducted on the Horizontal Grid at DPG, Utah. There were 49 rows and 40 lines of horizontal sampling positions, all at ground level, spaced at 15.2 meter intervals. The portions of the grid used in each trial varied as shown in Figures 1, 2, and 3.

Printflex card samplers were placed at every other grid sampling position, for a total of 625 sampling stations over the grid. Printflex is a paper that is somewhat more absorbent than Kromekote paper (Teske et al., 1993). The distance between sampling stations was 30.4 meters. Trial FS3 also had 141 special sampling stations with coated glass slides and spruce budworm larvae (SBWL) in petri dishes. Data from these special sampling positions were used to evaluate the effectiveness of Zectran® application and to indicate sampling density for later trials. These biological data provide a rare opportunity to look at model deposition patterns as a function of both card deposition and biological effectiveness. These data are not examined in this report, but in a separate report (MacNichol and Teske, 1994b), forthcoming.

2.3 Meteorological Measurements

A 48-meter profile mast located in the vicinity of the target array (Taylor et al. 1972) was instrumented to measure: wind speed at 0.5, 1, 2, 4, 8, 16, 30, and 45.7 meters above ground; wind direction at 2, 16, 32, and 48 meters above ground; temperature at 1 meter above ground; and temperature gradient between 0.5 meter and 1, 2, 4, 8, 16 and 32 meters above ground level.

Two-meter masts were located at each corner of the grid array to measure wind speed and direction (these four masts are indicated on Figures 1, 2, and 3).

Surface observations of dry and wet bulb temperature and cloud cover were taken 1500 meters northeast of the grid center, and pilot balloon (PIBAL) observations were taken at the same location (Taylor et al. 1972).

Table 2 summarizes the meteorological data available for trials of interest here. Two of the trials were conducted in the morning and one (FS3) in the early evening. Weather conditions remained similar throughout the day, with relative humidity at 28 to 29 percent and temperature between 6 and 11 degrees Celsius.

Wind speed data are available at 2 meters and at 48 meters, from 1.5 to 2.2 m/sec; wind speed readings are similar at both heights for each of the trials. Wind direction is only available at 2 meters and varied considerably over the three trials. Note that, while trials FS1 and FS2 were both intended to be inwind trials (Taylor et al. 1972), trial FS2 was flown with a 39 degree difference in wind direction and aircraft heading. Thus, FS2 is nearly a crosswind trial. Trial FS3, intended to be a crosswind trial, was flown with a 68 degree difference in wind direction and aircraft heading.

2.4 Spray Aircraft Configuration

The phase A trials were conducted with a C-47 cargo aircraft equipped with a FS spray system (Taylor et al. 1972). Table 3 summarizes the known aircraft and spray system characteristics.

Aircraft altitude above ground (spray release height) for the trials varied from 53 to 100 meters, as shown in Table 2. Aircraft spraying speed was 66.8 m/sec (130 kts) for all three trials. Aircraft heading is also shown in Table 2. As previously mentioned, aircraft heading and wind direction coincide in FS1 but not in the other two trials. Aircraft position over the grid can be seen in Figures 1, 2, and 3. The aircraft flew over the center of the grid in all three trials.

Spray material was released at the rate of 150 gal/min for 1 minute, starting 805 meters upwind of the grid. The spray material is described in detail by Taylor et al. (1972). The Zectran® FS-15 solution consisted of 24 ounces of Zectran® (4-dimethylamino-3, 5-xylyl methyl carbamate) in solution with one gallon of tri-propylene-monomethyl glycol ether (TPM). The spray material was a mixture of Zectran® FS-15 and either fuel oil or kerosene (one gallon of Zectran® FS-15 solution mixed with 9 gallons of either Number 2 Fuel Oil or odorless kerosene), dyed with Oil Red dye, chemical index (CI) 258 at 1.0 percent weight per volume. An estimate of the drop size distribution is shown in Table 4.

2.5 Data Reduction Procedure

Following each trial, the Printflex card samplers were collected, held until droplet stabilization (Taylor et al. 1972), then read. Visual observation and the Automatic Spot Counting and Sizing System (ASCAS, Young et al. 1977) were used to recover the droplet spectrum of the ground level deposition pattern. Card samplers from trials FS1 and FS2 appear to have been evaluated visually, while card samplers from trial FS3 were microfilmed, and sizing and counting were performed by the ASCAS. Taylor et al. (1972) noted that samplers at or near pattern center could not be processed by ASCAS due to droplet overlap, and that ASCAS estimates lacked definition for the outer areas of the deposition pattern and for areas of heavy deposition. Therefore, these estimates were adjusted to give more realistic estimates. Unfortunately, the accuracy of these adjustments is unknown.

Ground deposition data generated for trials FS1 through FS3 consist of predominant drop size (in micrometers) and deposition density (in mg/sq m). Contours of these three depositions are shown in Figures 4, 5 and 6. Note that the edges of the contours for all three trials are uneven, especially so for trials FS2 and FS3. Trial FS3 shows pockets of heavy deposition (denoted by letter E in Figure 6) surrounded by areas of lighter deposition. Such a contour pattern suggests turbulent atmospheric conditions, aircraft release height variability over the test grid, or spray system performance variability

during the test. Note also that some edges of the grid in trial FS3 are in areas of medium to high deposition (letters C and D in Figure 6), indicating that the entire swath was not captured on the grid. Pattern edge effects are discussed in detail in MacNichol and Teske (1994b).

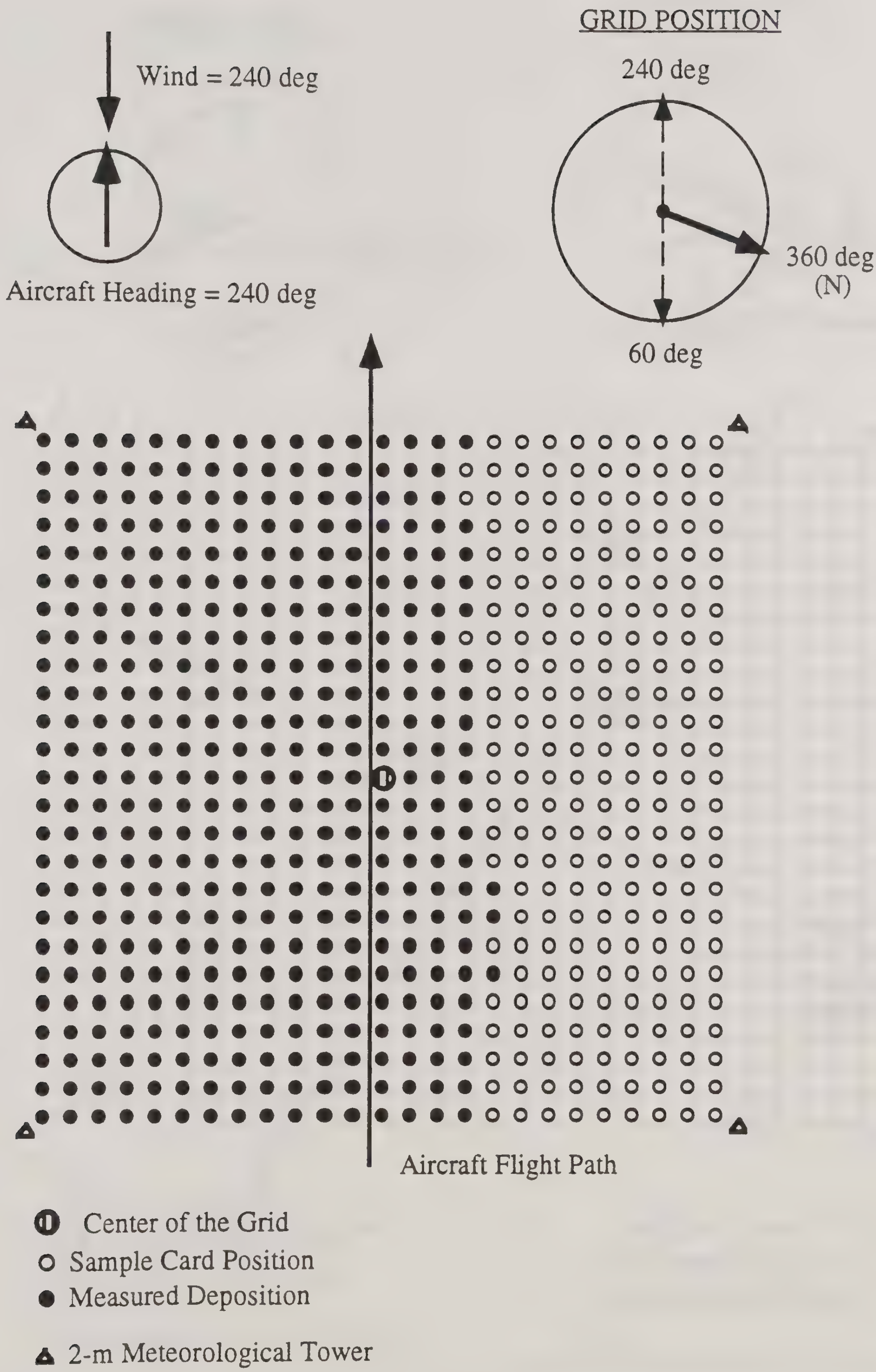


Figure 1: Horizontal Grid at Dugway Proving Ground for FS1

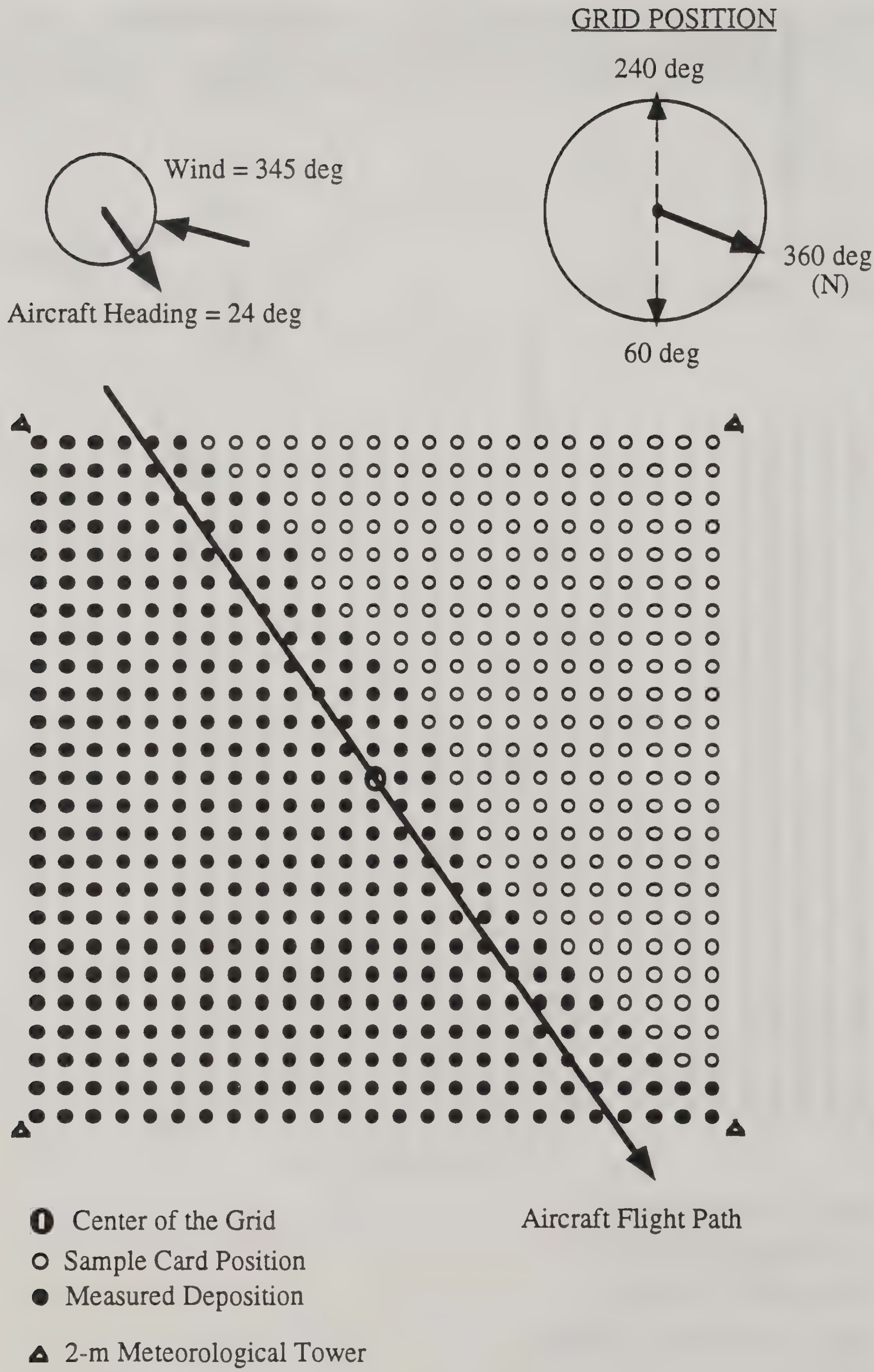


Figure 2: Horizontal Grid at Dugway Proving Ground for FS2

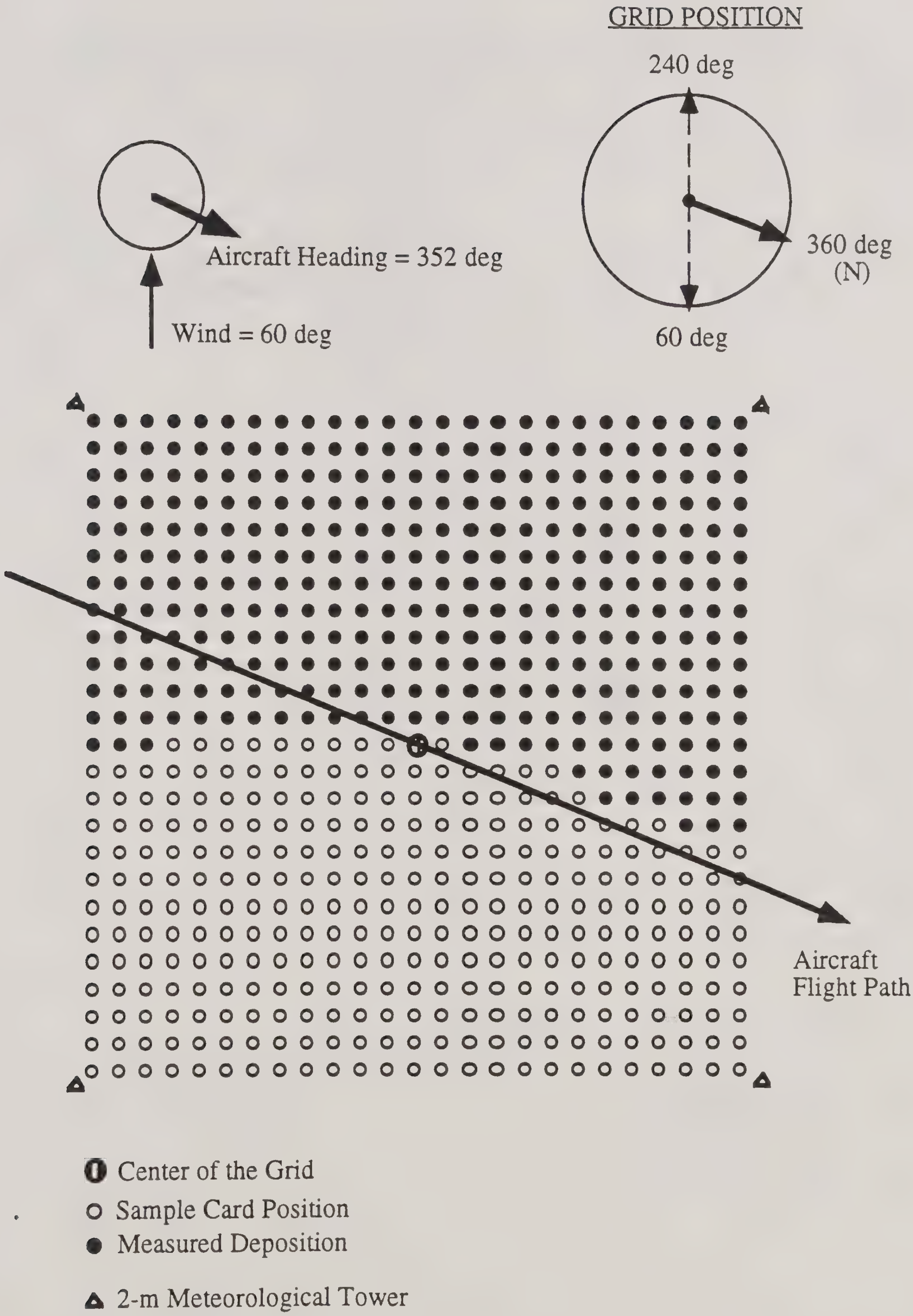
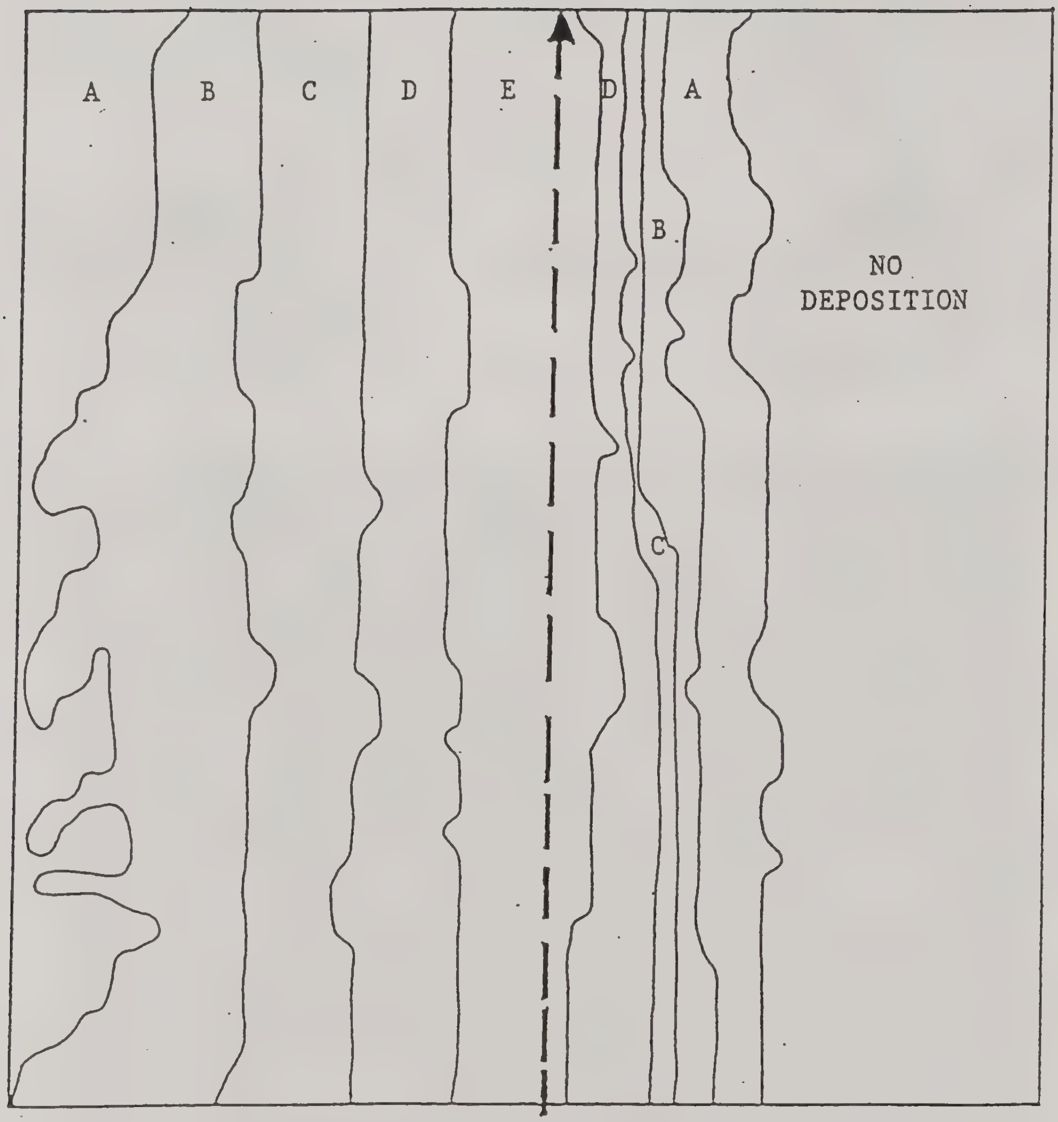


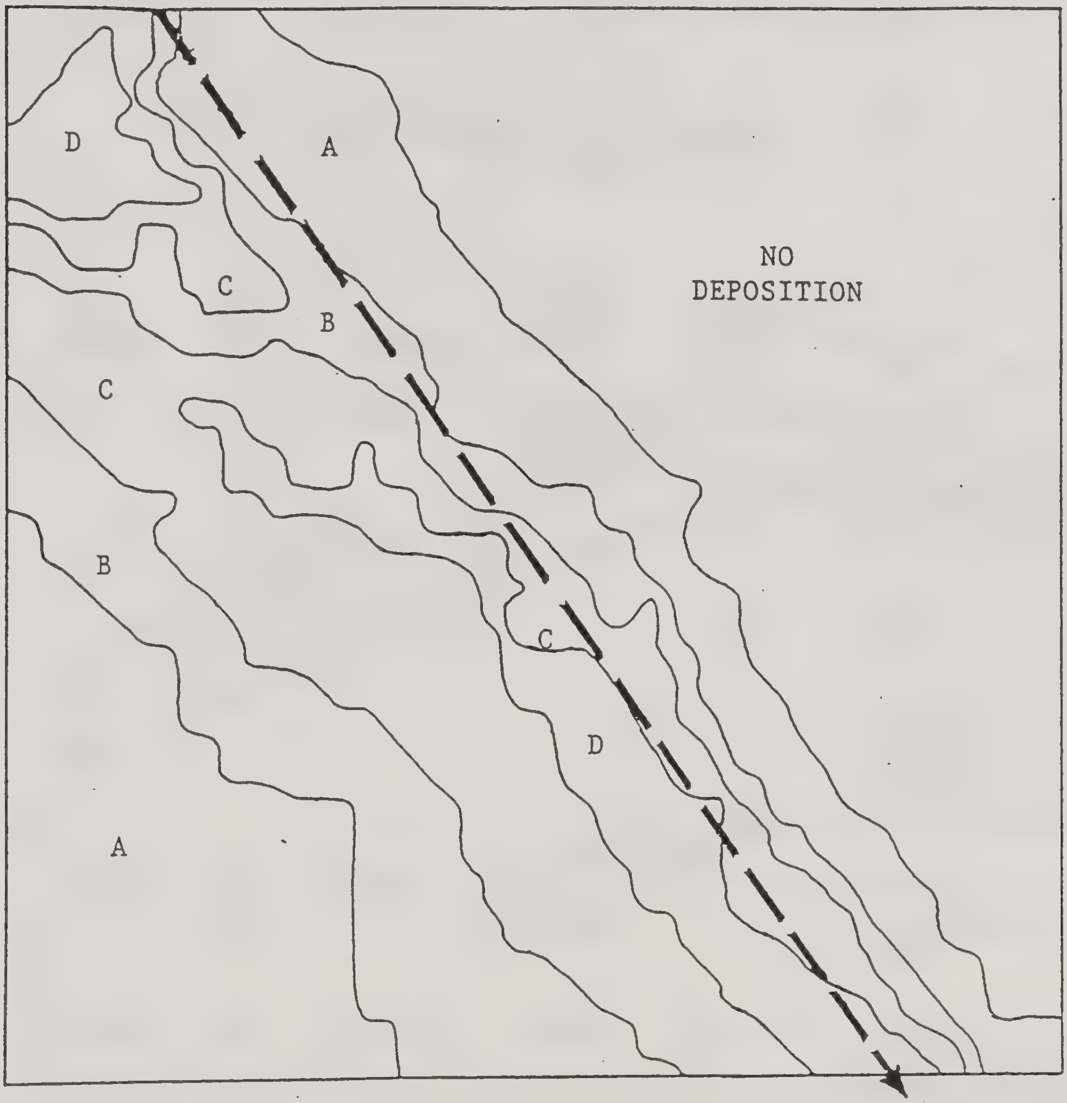
Figure 3: Horizontal Grid at Dugway Proving Ground for FS3



FLIGHT LINE

A 1 - 29 mg/sq m Deposition Density
B 30 - 80 mg/sq m " "
C 90 - 170 mg/sq m
D 180 - 390 mg/sq m
E 400 - 900 mg/sq m

Figure 4: Deposition Contour for Trial FS1 (Horizontal Grid at Dugway Proving Ground)



FLIGHT LINE

A 1 - 80 mg/sq m Deposition Density
B 90 - 170 mg/sq m " "
C 180 - 350 mg/sq m
D 360 - 700 mg/sq m

Figure 5: Deposition Contour for Trial FS2 (Horizontal Grid at Dugway Proving Ground)

FLIGHT LINE

A 1 - 10 mg/sq m Deposition Density
B 20 - 80 mg/sq m " "
C 90 - 170 mg/sq m
D 180 - 390 mg/sq m
E 400 - 800 mg/sq m

Figure 6: Deposition Contour for Trial FS3 (Horizontal Grid at Dugway Proving Ground)

Table 1: Scope of the 1972 MISS test

Test Phase	Spray System	Trial No.	Location	Date of Trial	Release Ht (m)	Purpose
A	FS	FS1 FS2 FS3	DPG	27 April 27 April 27 April	150 - 300	Establishment of a baseline with the FS system compatible with Zectran® spray license criteria. Deposition density, area coverage, droplet spectra, liquid recovery and swath width evaluated. Petri dishes containing spruce budworm larvae were placed at special sampling positions during Trial FS3 to evaluate Zectran® effectiveness.
B	MISS	FS4 FS5	DPG	24 June 24 June	150 - 300	Preliminary trials: deposition characteristics of the MISS system
C	MISS	FS6	DPG	25 June	150 - 300	Comparison with the baseline established in Test Phase A to demonstrate that the MISS system meets Zectran® license criteria
D	MISS	FS7	Lolo National Forest	29 June	145 - 150	Demonstration of the effectiveness of the MISS system to suppress spruce budworm larvae in an infested coniferous forest

Table 2: Summary of meteorological data and spray system variables for trials FS1, FS2, and FS3

	FS1	FS2	FS3
Time of Day (MST)	07:17	09:15	18:22
Relative Humidity (percent)	28	28	29
1-m Air Temperature (deg C)	6.7	11.06	6.1
Temperature Difference (0.5 to 32 m) (deg C)	-2.5	-2.1	0.0
2-m Wind Speed (m/sec)	1.5	2.0	2.2
48-m Wind Speed (m/sec)	1.5	2.2	2.0
2-m Wind Direction (deg)	240	345	60
Aircraft Heading (deg)	240	24	352
Aircraft Height (m)	53.0	61.9	100.0

Table 3: Aircraft characteristics for trials FS1, FS2 and FS3

Aircraft Type	C-47
Weight (kg)	9702.0
Wing Span (m)	28.82
Planform Area (sq m)	93.79
Drag Coefficient	0.1
Propeller Radius (m)	1.77
Propeller Efficiency	0.8
Blade RPM	2550.0
Number of Nozzles Assumed	46
Nozzle Type Assumed	8020
VMD Assumed (μm)	211.1
Flow Rate (gal/min)	150.0
Spraying Speed (m/sec)	66.82

Table 4: Drop size distribution assumed for trials FS1, FS2, and FS3

Drop Diameter (micrometers)	Mass Fraction
45.88	0.0115
73.73	0.0274
106.35	0.0521
138.62	0.1180
171.03	0.1649
203.42	0.1674
235.88	0.1698
268.32	0.0843
301.32	0.0267
334.77	0.0435
366.72	0.0080
398.21	0.0145
430.71	0.0358
463.18	0.0422
495.68	0.0014
528.67	0.0325

	1.0000

3. Statistical Analysis of Deposition Data

The approach taken in this report is to examine the three data sets (FS1, FS2, and FS3) with accepted statistical methods, in an effort to understand the accuracy, repeatability and confidence of the multiple card line deposition data.

3.1 Definition of Terms

The uncertainty in a measurement process is expressed as experimental error and is a statistical property of that process. Because measurements are carried out on specific systems, experimental error depends on the system being measured as well as the measurement process itself, and can seldom be adequately characterized by a single number. Thus, experimental error is usually expressed in terms of the concepts of *precision* and *accuracy*. Any elementary statistics text addresses the concept of experimental error (for example, Guttman et al. 1971, Larson 1974, Box et al., 1978, or Mandel 1964). For the purpose of clarity, the terminology used in this report is briefly defined in this section, before analyzing the deposition data from trials FS1, FS2, and FS3.

A *population* is a total set of N observations. A *sample* is a small group of n observations actually available. The *mean* of the population is designated by μ, while the *sample average* is designated by $\bar{y}$ (Box et al. 1978). The *population variance* is designated by σ^2, and the *sample variance* is designated s^2. Assuming that deposition at each point on the x-axis is a normally distributed random variable y, the sample average, $\bar{y}$, and variance, s^2, are unbiased *point estimators* for the population mean, μ, and the population variance, σ^2 (Guttman et al. 1971).

The term *precision* of a measurement addresses its repeatability: given a well-described experimental procedure for measuring a characteristic of a physical system, the precision of the measurement depends on the amount of scatter exhibited by the results obtained through repeated application of the process to that system (Mandel, 1964). The more *precise* the experimental process, the less scatter in the results. In the Phase A trials, precision of the testing process depends on repeatability of the data measurements as well as repeatability of the test conditions.

To express the *accuracy* of a measurement, a reference value for the measurement must be established. This reference value, R, is then compared to the mean of the population, μ. The accuracy of the experimental process can be expressed as the difference between the population mean and the established reference value (Mandel calls this difference the bias of the process). It is useful to think of darts thrown at a bulls-eye: in Figure 7a, the cluster of darts can show good precision without being accurate. Figure 7b shows a cluster of darts which is accurate but not very precise (the mean position of the darts is close to the bulls-eye, but there is still a lot of error).

Experimental error is limited by both precision and accuracy.

If multiple occurrences of the same measurement are available (i.e.., if there is a sample of size $n > 1$), experimental error can be quantified and expressed by the point estimators described above. The precision of these point estimators can be expressed by *interval estimators*, one of which, the *confidence interval for the mean,* will be defined in

the following sections. When comparing deposition predicted by mathematical models to field test results, interval estimators can be especially useful. They provide a means to evaluate a degree of confidence in the field test deposition data, and thus help to evaluate the quality of the prediction.

3.2 Sources of Error

A statistical analysis of the 1972 MISS test must start with an identification of possible sources of experimental error in the test procedure. The data of interest is deposition (in mg per sq m) at specific sampling positions on the ground.

Deposition on a card is determined by assessing the number of droplets that have impacted on the card. The accuracy of the deposition data on a given card depends only on the accuracy of this assessment (in other words, on the accuracy of the instruments or techniques used). In this case, all cards were read either with the ASCAS or visually, and this reading was then used to assess deposition on each card (there was no laboratory assay to determine mass). There is no way to assign a level of accuracy to the method used to read the cards since a significant aspect of this method involved human judgment.

What is actually being read is the number of stains on the card; drop size is determined from stain size by applying an expression for the spread factor of the formulation being sprayed (Teske et al., 1993). The accuracy of the spread factor expression, in this case for Zectran® FS-15, is another possible source of error in the recovery of deposition on each card. In this test, the accuracy of the spread factor expression used to assess the number of drops on a card is also unknown (although the expression itself is given by Taylor et al., 1972).

The precision of the deposition data on a card is a repeatability issue. Repeatability of the deposition measured on a single card can be determined if there are multiple cards at the same axial distance from the flight line. This aspect of the experimental error can be addressed with the data from the MISS test since the deposition data is available over a large grid.

The deposition profile is determined from a line of sample cards. In addition to the experimental error that results from measuring deposition on each card, there is the issue of repeatability of the test conditions over the entire card line. Variable test conditions (such as a variation in aircraft height or wind direction over the length of the card line) can be a source of error, especially in these tests because the test grid is so large. More than one trial conducted under the same (or very similar) test conditions would address this type of repeatability error. Since each trial in the MISS test was conducted under different conditions, this aspect of the experimental error cannot be addressed either.

The accuracy of instruments used to measure test conditions can also be a source of error when considering the deposition profile. Again, this aspect of experimental error in the MISS test is unknown.

To summarize, sources of error in the MISS test include the following:

1. Methods used to count and size stains deposited on the sampler cards can not be adequately assigned any degree of accuracy.

2. Other measurement techniques (such as length of time involved in obtaining drop measurements and methods used to generate mass deposition data) also can not be assigned any degree of accuracy.

3. The accuracy of test conditions that may cause variation from one card line to another (such as aircraft height over the test grid and meteorological variations) is not known.

Taylor et al. (1972) does not address the first two points above, which describe the accuracy of data measurement on the test grid. The third point, which describes the accuracy of measured test conditions, is also not addressed. As noted above, these aspects of the experimental error are unknown. Furthermore, since only one set of data is available for each trial, the repeatability of the data for a given set of test conditions is also unknown.

The only aspect of experimental error in the MISS test which can be addressed is that of repeatability of measured deposition normal to the aircraft flight path; this statistical analysis is the subject of this report.

Deposition data are available over a large grid and can be organized into many card lines normal to the aircraft flight path. When so organized, data are available for a specific set of positions along the card lines, and these positions are the same for all card lines. Thus, Figure 8 shows all of the deposition data from trial FS1 (on the y-axis) along a line normal to the aircraft flight path (the x-axis, where $x = 0$ is at the aircraft centerline). Assuming that the test conditions do not change during the spray pass (i.e., that aircraft and spray variables and meteorological conditions are constant over the test grid), the deposition data from all card lines should be the same; the scatter in measured deposition at specific points along the x-axis indicates the precision of the data measurement at those points.

3.3 Analysis Using Trial FS1

As previously mentioned, deposition over the test grid can be represented by 25 card lines for trials FS1 and FS2 and 16 card lines for trial FS3. The deposition data shown at each point represent a sample (assumed to be a random sample) of the population of possible values of deposition at that point. An average value for deposition, $\bar{y}$, can be calculated at each of these points, and the corresponding deposition profile will be referred to as the average deposition profile. The average profile for FS1 is shown in Figure 9. Deposition is available at discrete points along the x-axis. It is assumed that the average deposition at these discrete points can be interpolated to give an average deposition profile at all points of interest.

The sample *standard deviation*, s, is a common way to measure the precision (or the scatter) of the deposition measurements at each point. The *relative standard deviation*, RSD, is the standard deviation s divided by the average $\bar{y}$. Figure 10 shows the relative standard deviation of deposition data at specified distances along the x-axis. A quick prediction of swath width can be made by determining the positions of half-deposition on either side of the peak from the average deposition profile curve in Figure 9. All data points within this predicted swath (from 80 meters to the left of the aircraft centerline to 40 meters to the right of the aircraft centerline) are designated *in-swath*.

Note that values of RSD are much lower in-swath than farther out-of-swath; thus, the relative scatter in measured deposition is smaller in-swath. Repeatability of data

measurement on a card should be independent of variation in test conditions (since only a single card is considered); therefore, it should be independent of location on the card line. However, data reduction probably reflects the error inherent in the measurement method, in this case a combination of visual measurement and the ASCAS. As previously mentioned, ASCAS estimates lacked definition for the outer areas of the test grid, where there was a preponderance of smaller droplets (≤ 60 microns in size); the ASCAS estimates were adjusted in a way that was not described. These outer areas of the test grid correspond to the out-of-swath points on the x-axis in Figure 10, and reflect higher RSD values accordingly.

To represent the relative scatter of all the data points in-swath with a single value, the sample standard deviations for all the in-swath points are *pooled* as follows:

$$s = \sqrt{\frac{\sum_{i=1}^{g} v_i s_i^2}{\sum_{i=1}^{g} v_i}}$$

where g represents the number of points on the x-axis to be pooled ; s^2 is the sample variance at a specific point; and v represents the degrees of freedom at that point (for a sample of size n, $v = n-1$). A pooled standard deviation is appropriate when the variation at each axial point is expected to be the same (i.e.., test conditions and measurement variations are constant over the grid). For trial FS1, $v = 24$ for all points in-swath (each axial position represents a sample of 25 deposition measurements). The pooled in-swath RSD for trial FS1 is 0.22.

The point estimators $\bar{y}$ and s calculated so far are commonly recognized statistics. A point estimator is the best single value which estimates the unknown true value of a population parameter. For the data at hand, $\bar{y}$ is the best estimator of the true mean deposition, μ, at a given point, although it might not be a very close estimate of μ.

It is possible to assess the probability that the true value of μ is within a given range of its estimator. A $100(1-\alpha)\%$ *confidence interval* for the population mean μ is an interval bracketing the known sample average $\bar{y}$. This statistic indicates that, over the long term, $100(1-\alpha)$ percent of the times that the experiment is repeated the population mean μ will lie within this interval. More exactly, if $\bar{y}$ and s^2 are the mean and variance of a sample of size n from a normal distribution $N(\mu,\sigma)$, where the population parameters μ and σ are unknown, then

$$\bar{y} \pm t_{n-1;\alpha/2} \frac{s}{\sqrt{n}}$$

is a $100(1-\alpha)\%$ confidence interval for μ. The parameter t is the Student t distribution for $(n-1)$ degrees of freedom and α.

Assigning a level of statistical certainty to test data is particularly useful when comparing mathematical simulations of deposition for given test conditions to actual field test data. The quality of the simulation can be assessed based on whether it falls within a specified confidence interval for the mean. MacNichol and Teske (1994b) examine the

same MISS data used in this report and evaluate FSCBG simulations of the test data using a 95% confidence level for the mean deposition.

Figure 11a shows confidence intervals bracketing a portion of the average deposition profile for FS1. For a given standard deviation and sample size, the interval becomes larger as the confidence level increases. A larger interval is necessary to bracket the true mean 95% of the time than would be necessary to bracket the true mean only 75% of the time. At a given level of confidence and for a given number of samples, the smaller the interval, the more precisely the sample average is estimating the population mean.

In this report we have chosen to interpret the FS1, FS2 and FS3 field data with a 95% confidence interval. A typical confidence interval for field data is 90 percent (Teske 1992); however, for this analysis a higher confidence level was used. Confidence level is selected based on how important it is to know value limits, in this case the limits of the mean deposition profile. Because the data examined here will also be compared to mathematical predictions of deposition for the given test conditions (MacNichol and Teske, 1994b), the value limits are very important.

The second term in the above definition of a confidence interval gives the *range for the mean at 100(1-α)% confidence*, $t_{n-1;\alpha/2} \frac{s}{\sqrt{n}}$. Figure 11b illustrates the range for the mean at a given level of confidence.

For a given level of confidence (95% for this report), this range depends on the standard deviation, s, and on the number of samples, n (for a given α, the value of the t distribution depends only on n). When the standard deviation is given, the range for the mean depends only on the number of samples, in our case the number of card lines used to generate deposition data. A table of the t distribution (which can be found in any statistics text) shows that, for a given α, the value of t is greater at small n ($n<5$) and approaches a constant value for large n ($n>60$). The range for the mean also depends on the reciprocal of the square root of n.

Figure 12 shows a 95% confidence interval ($\alpha = 0.05$) bracketing the average deposition profile of trial FS1. It is assumed that confidence intervals generated at discrete points along the x-axis can be interpolated to give a confidence interval for the entire deposition profile. Note that the size of this interval is not constant along the profile, because the standard deviation, s, changes for each point along the x-axis. For this example, $n = 25$ and $t_{n-1;\alpha/2} = 2.064$ (from tables). The confidence interval shown can be interpreted to mean that if there were 100 samples of deposition data recovered under exactly the same conditions (so that the only error to be evaluated was measurement error), the mean deposition μ would fall within this interval 95% of the time.

It is useful to nondimensionalize the confidence interval calculation by dividing by the mean deposition, $\bar{y}$. The normalized range for the mean then becomes $t_{n-1;\alpha/2} \frac{RSD}{\sqrt{n}}$ Figure 13 shows the normalized range for the mean at 95% confidence for the deposition from trial FS1, at the pooled in-swath $RSD = 0.22$. This figure shows that as the number of samples (or card lines) increases, the normalized range for the mean decreases. Conversely, as the number of card lines decreases, the normalized range for the mean becomes very large, and at $n = 3$ the range begins to increase exponentially.

The range for the mean is a measure of the precision of the estimate for the population mean. As the range increases sharply, the precision of the estimate decreases accordingly. For the purposes of this analysis, we define the minimum acceptable number of samples to be at the point where the normalized range for the mean begins to increase sharply. Figure 13 indicates that, subject to the assumptions made so far for trial FS1, at a 95% level of confidence the interval bracketing the average deposition profile grows exponentially when the profile is generated from fewer than three samples at each axial position. This statement addresses only the measurement repeatability at axial points along the card line.

3.4 Analysis Using Trial FS2

Figure 14 shows the grid deposition data for trial FS2, normal to the aircraft flight line (the aircraft is flying over x = 0.0). This trial is nearly a crosswind trial: a 39 degree difference between wind direction and aircraft heading was recorded. Comparing Figures 8 and 14, there is considerably more scatter in the deposition data for trial FS2 than for trial FS1. However, since the aircraft flew at an angle to the established grid lines, these data must be interpolated back to a uniformly spaced grid, for the purposes of our analysis. This manipulation of the data, and an average deposition profile are shown in Figure 15.

The relative standard deviation along the x-axis for FS2 is shown in Figure 16. There appears to be more scatter in the data than for FS1, and values of RSD in-swath are not as low as the in-swath RSD values for that trial. The pooled RSD in-swath (from 0 to 180 meters) is calculated to be 0.45.

Figure 17 shows the 95% confidence interval bracketing the average deposition profile for trial FS2. As mentioned, there is more scatter in the deposition data from this trial than there is in the data from FS1, thus the width of the confidence interval is considerably larger. Because the average profile was generated from data with more scatter, it takes a larger interval to ensure that the true population mean is bracketed 95% of the time.

The plot of normalized range for the mean at 95% confidence (Figure 18) also reflects the increased scatter in the data from this trial. At the 95% level of confidence, four or more card lines are necessary to achieve a "good" estimate of the average deposition profile for trial FS2.

3.5 Analysis Using Trial FS3

Figure 19 shows the grid deposition data for trial FS3, normal to the aircraft flight line. This trial is a crosswind trial with a 68 degree difference between wind direction and aircraft heading. Comparing Figures 8, 14 and 19, there is still more scatter in the deposition data for trial FS3 than for trial FS1; there is less of a difference in the amount of scatter between trials FS2 and FS3. Interpolated data and the average deposition profile are shown in Figure 20. Because this is a crosswind trial, the swath (as determined with the procedure described for FS1) is much wider than for either of the other two trials.

The relative standard deviation along the x-axis for FS3 is shown in Figure 21. There is quite a lot of scatter in the data, and values of RSD in-swath (from -285 to 75 meters) are high. RSD remains between 0.20 and 0.60 for much of the deposition profile. The pooled RSD in-swath is calculated to be 0.50. Note that this value is not

much higher than the pooled RSD in-swath for FS2. Although the shape of the average deposition profile is considerably different for this trial, the amount of scatter apparent in the deposition data is similar to the amount of scatter in the data from FS2.

Figure 22 shows the 95% confidence interval bracketing the average deposition profile for trial FS3. Again, there is more scatter in the deposition data from this trial than there is in the data from FS1, thus the width of the confidence interval is considerably larger. In this trial, the greatest amount of scatter occurs downwind of the aircraft flight line, from -400 to -100 meters, and the confidence interval is widest there.

The plot of normalized range for the mean at 95% confidence (Figure 23) also reflects the large amount of scatter in the data from this trial. At the 95% level of confidence, four or more card lines are necessary to achieve a "good" estimate of the average deposition profile for trial FS3 (the same number as for trial FS2).

3.6 Results

The analysis above suggests a means of improving statistical confidence in deposition data recovered from sample cards even though it was only possible to assess one aspect of experimental error in the trials examined. As long as multiple measurements of deposition data are available for points parallel to the flight path, it is possible to establish a level of confidence in the measurement of the average profile generated from that data. Obviously, the more measurements available at a given distance from the flight line, the more precise the estimate of the mean deposition profile at that distance is likely to be. Data from this test indicate that, to be 95% confident that the true mean deposition will be within 50% of the measured average deposition, at least three measurements at points in-swath are needed when the trial is inwind, and four measurements are needed when the trial is crosswind.

Since the analysis presented shows that the standard deviation of data at points along an axial line of deposition can be pooled, multiple samples at a few representative distances from the aircraft flight path should be sufficient to assign a level of confidence to the field test data. Entire card lines need not be duplicated. A test design which incorporates this idea is described in the Appendix.

A few points regarding confidence intervals should be noted. First, the interval which establishes a degree of precision for the mean is entirely a function of the number of card lines (n), the standard deviation (s), and the level of confidence desired. For a given number of card lines and for a given level of confidence in the mean, the precision of the estimate of the mean can only be improved by decreasing the standard deviation (or the experimental error). Recommendations regarding this issue are made in the conclusions section of this report.

Secondly, if the experimental error and the number of card lines used are given, decreasing the level of confidence in the mean will decrease the width of the confidence interval. However, it is not good procedure to adjust the confidence interval to give a desired range: a lower level of confidence decreases the amount of certainty that the true mean deposition for the given test conditions falls within the bracketed interval. At the new level of confidence, the precision of the estimate of the mean is still determined by the existing experimental error and by the number of card lines used in the test.

Finally, the above analysis notwithstanding, the best estimate of the mean deposition for a given set of test conditions is still the data mean. Confidence interval

calculations are an indication of the precision of this estimate. If only one card line is used, data from that card line is the best estimate of the deposition profile, but no level of certainty can be assigned to the estimate unless the repeatability of data measurement is addressed.

To review the assumptions which have been made in this section:

1. Test conditions (aircraft and spray variables and meteorological conditions) are constant over the test grid.

2. Measurement techniques are constant over the grid.

3. The deposition at each point on the x-axis is a random sample of the population of possible values of deposition at that point. It is a normally distributed random variable y ; $\bar{y}$ and s^2 are the average and variance of a sample of size n from a normal distribution $N(\mu,\sigma)$, where μ and σ are unknown.

4. Deposition is available at discrete points along the x-axis. It is assumed that the average deposition at these discrete points can be interpolated to give an average deposition profile at all points of interest. Similarly, confidence intervals generated at discrete points along the x-axis can be connected to give a confidence interval for the entire deposition profile.

5. In-swath data is designated by that portion of the average deposition profile which falls within half the peak deposition value.

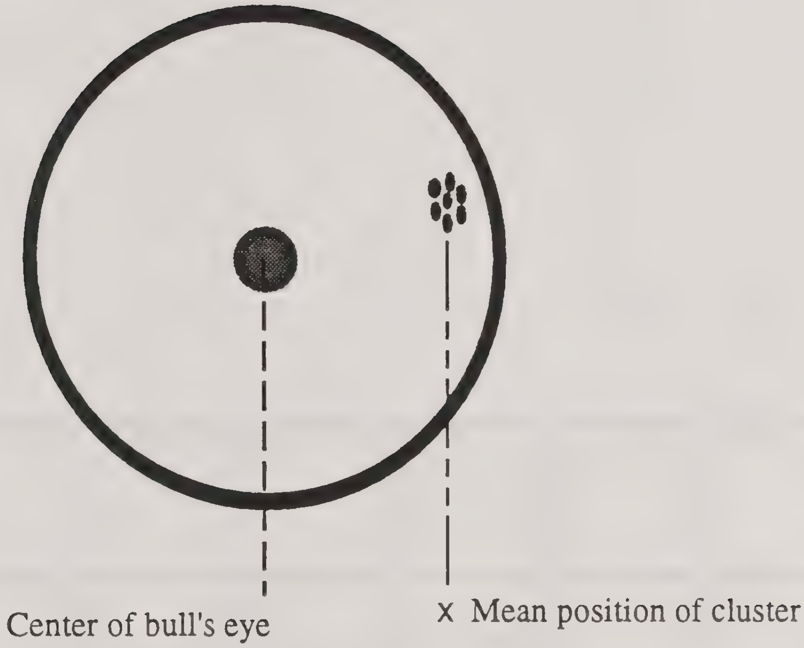


Figure 7a: The position of points in the cluster of darts has precision but not much accuracy.

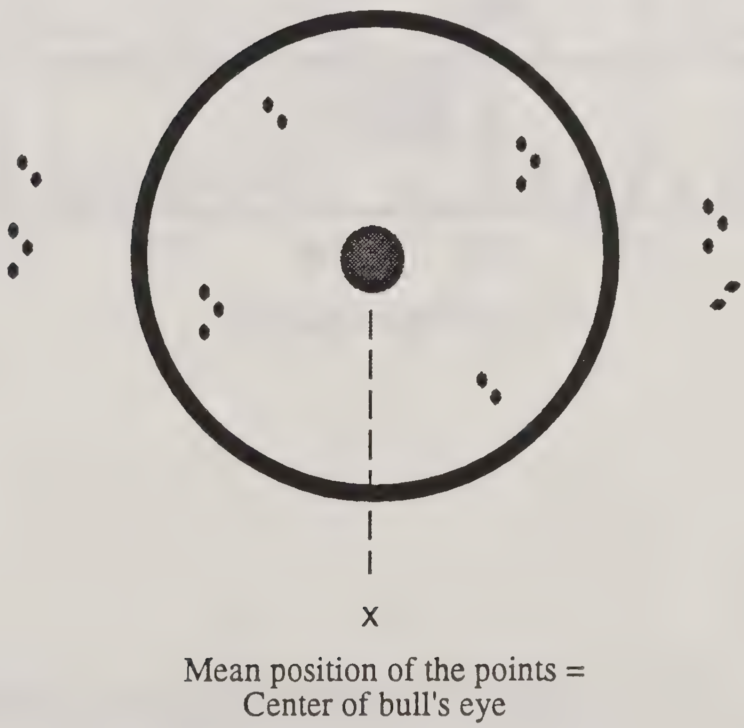


Figure 7b: The position of points in the cluster of darts has accuracy but not much precision.

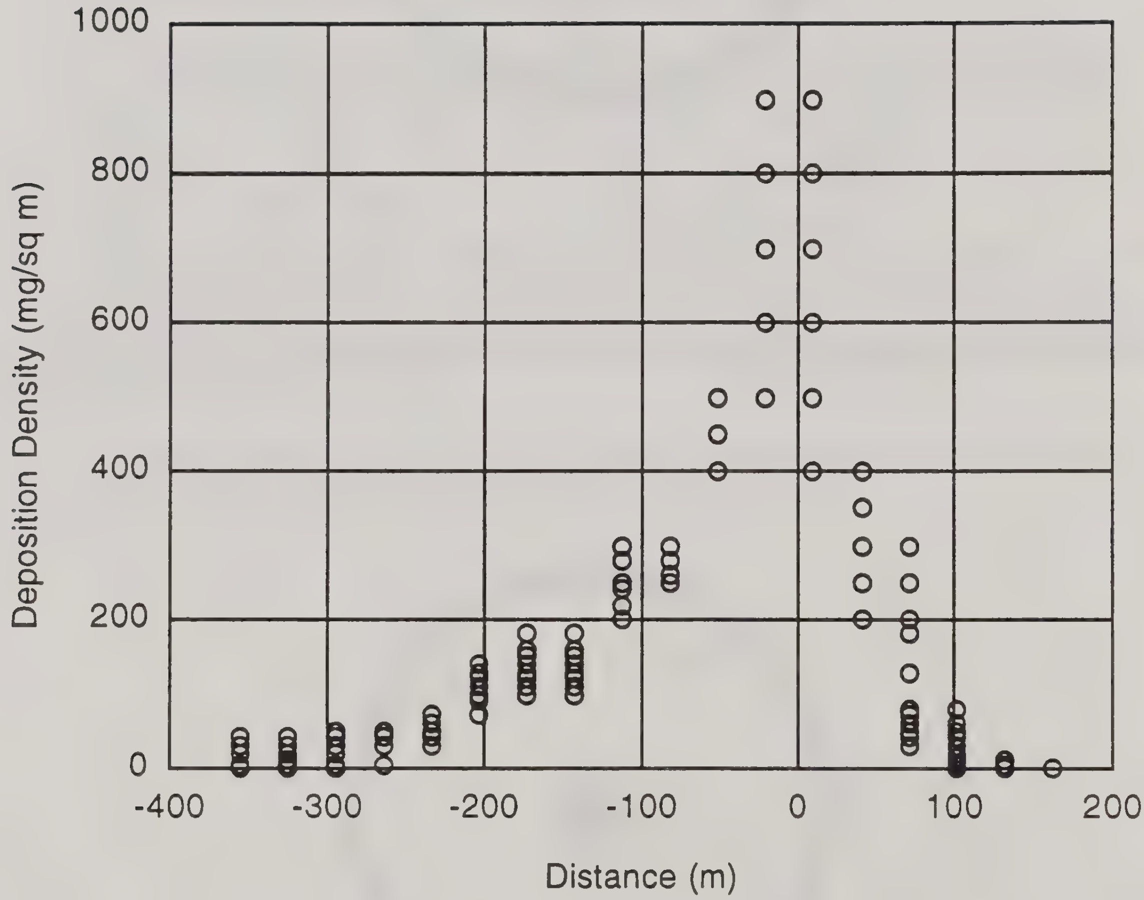


Figure 8: Deposition Data for Trial FS1. The aircraft is passing over x = 0 with negative Distance to the left of the aircraft centerline, and positive Distance to the right of the aircraft centerline.

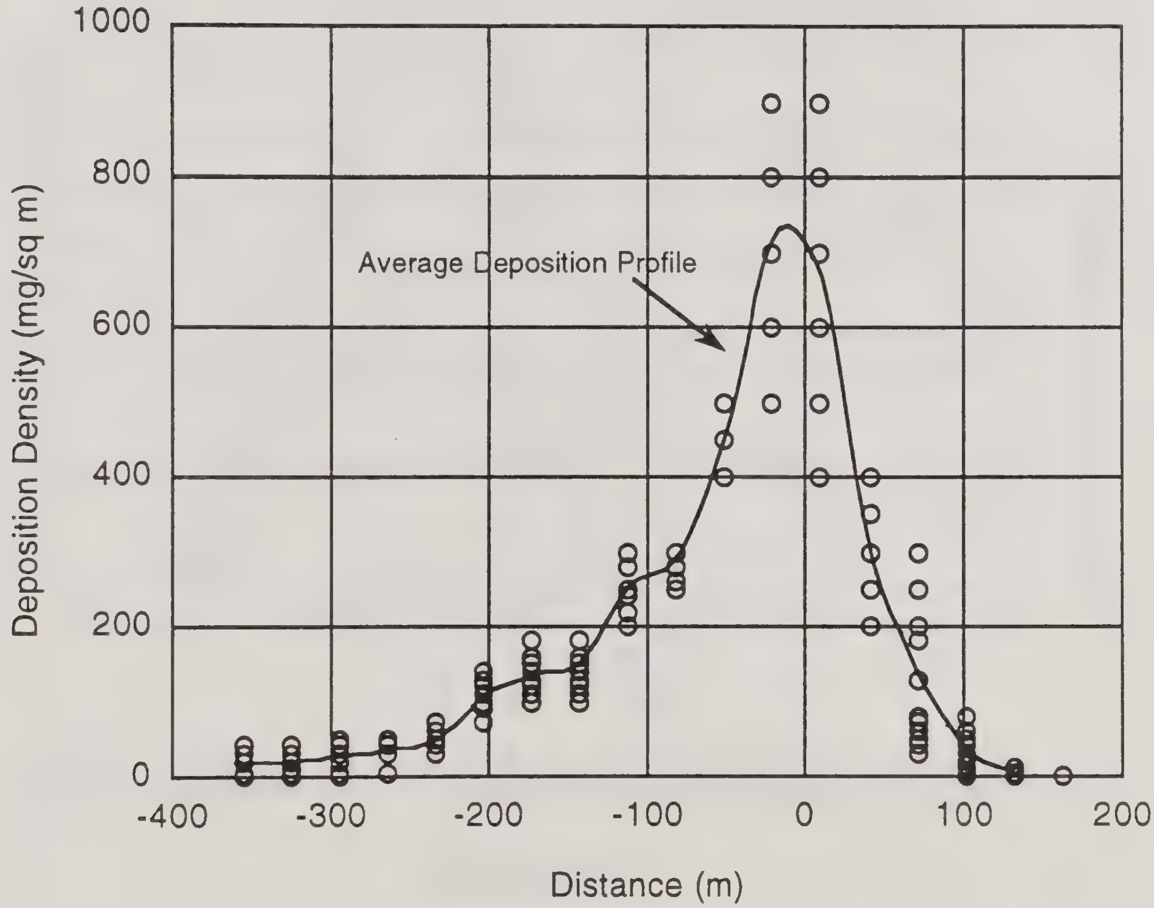


Figure 9: Average Deposition Profile for Trial FS1 (Smoothed)

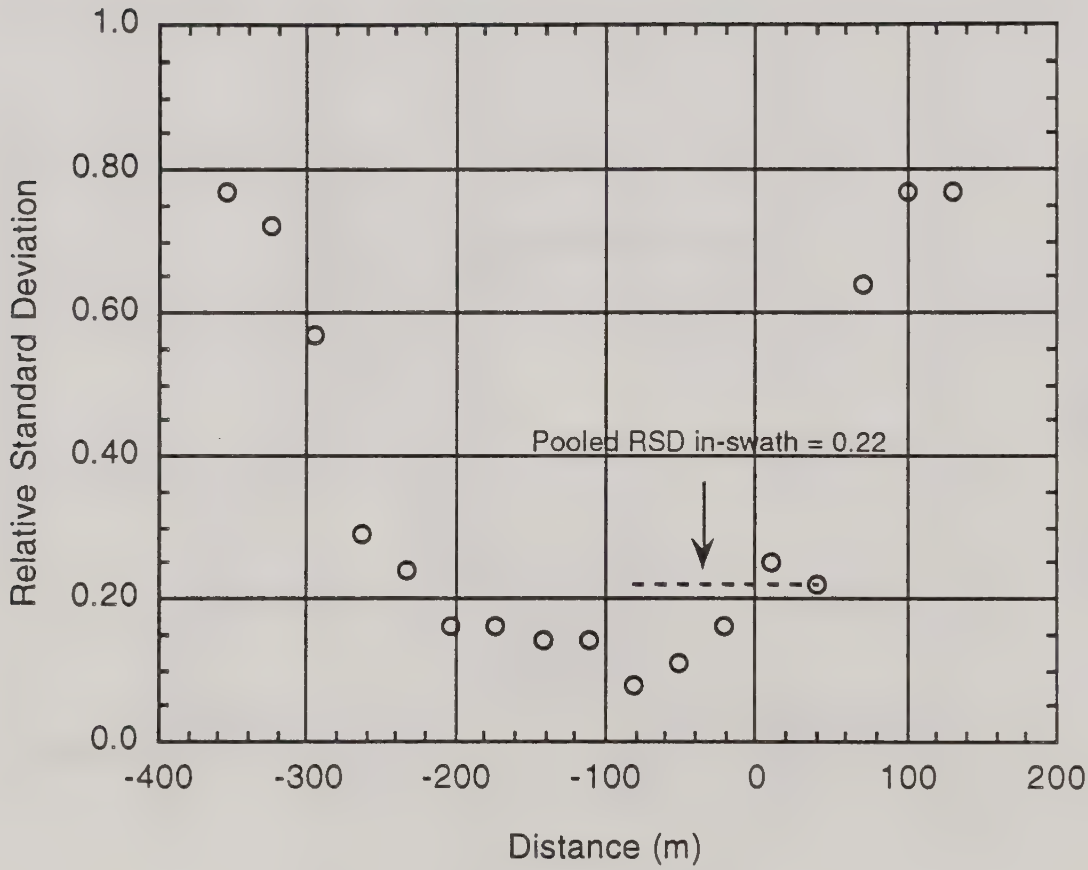


Figure 10: Relative Standard Deviation of Deposition for Trial FS1

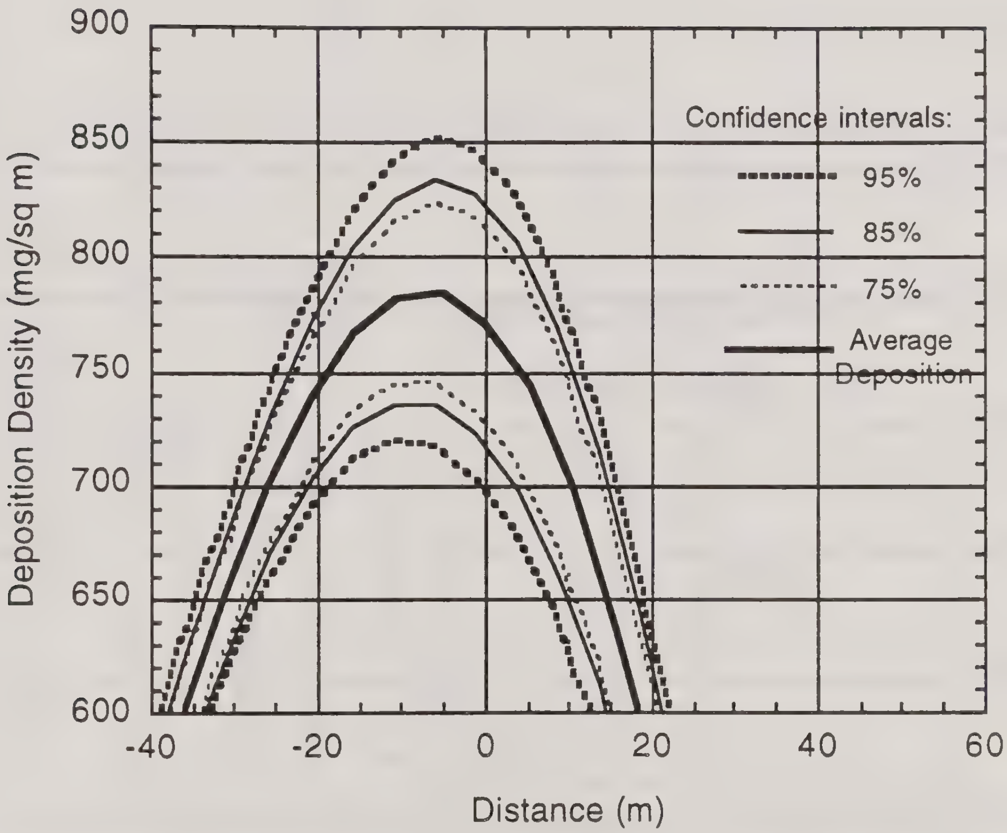


Figure 11a: Confidence Intervals Bracketing the Average Deposition Profile of FS1

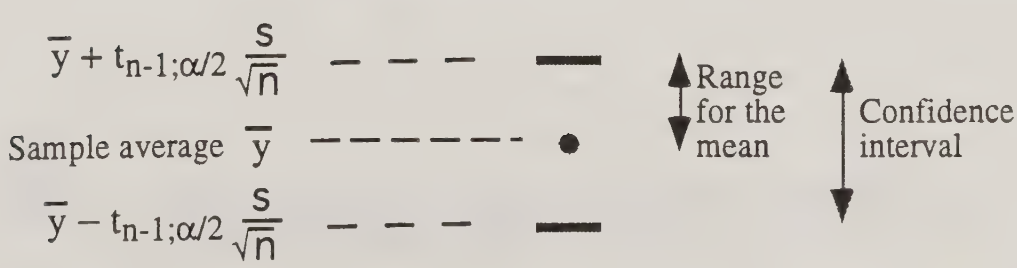


Figure 11b: Confidence Interval Length and Range for the Mean

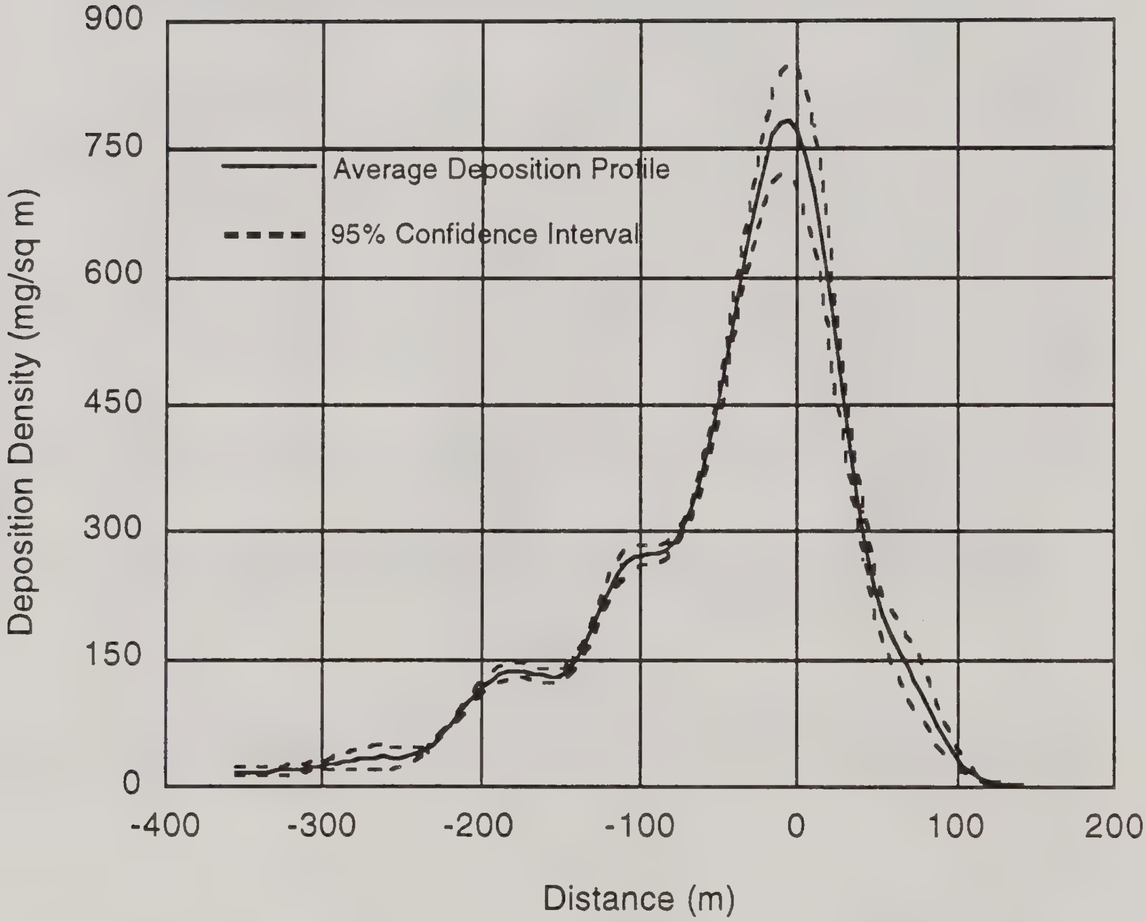


Figure 12: 95% Confidence Interval Bracketing the Average Deposition Profile for FS1

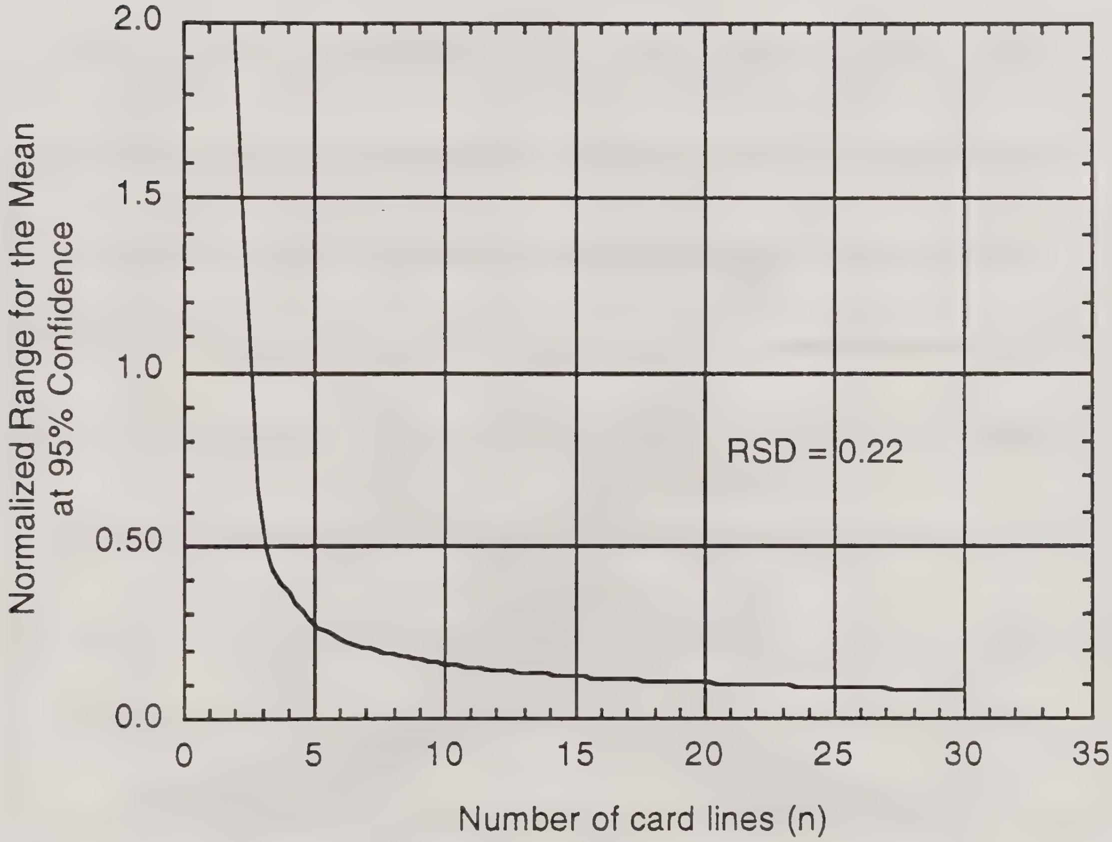


Figure 13: Normalized Range for the Mean Deposition at 95% Confidence, for pooled in-swath RSD = 0.22 , FS1

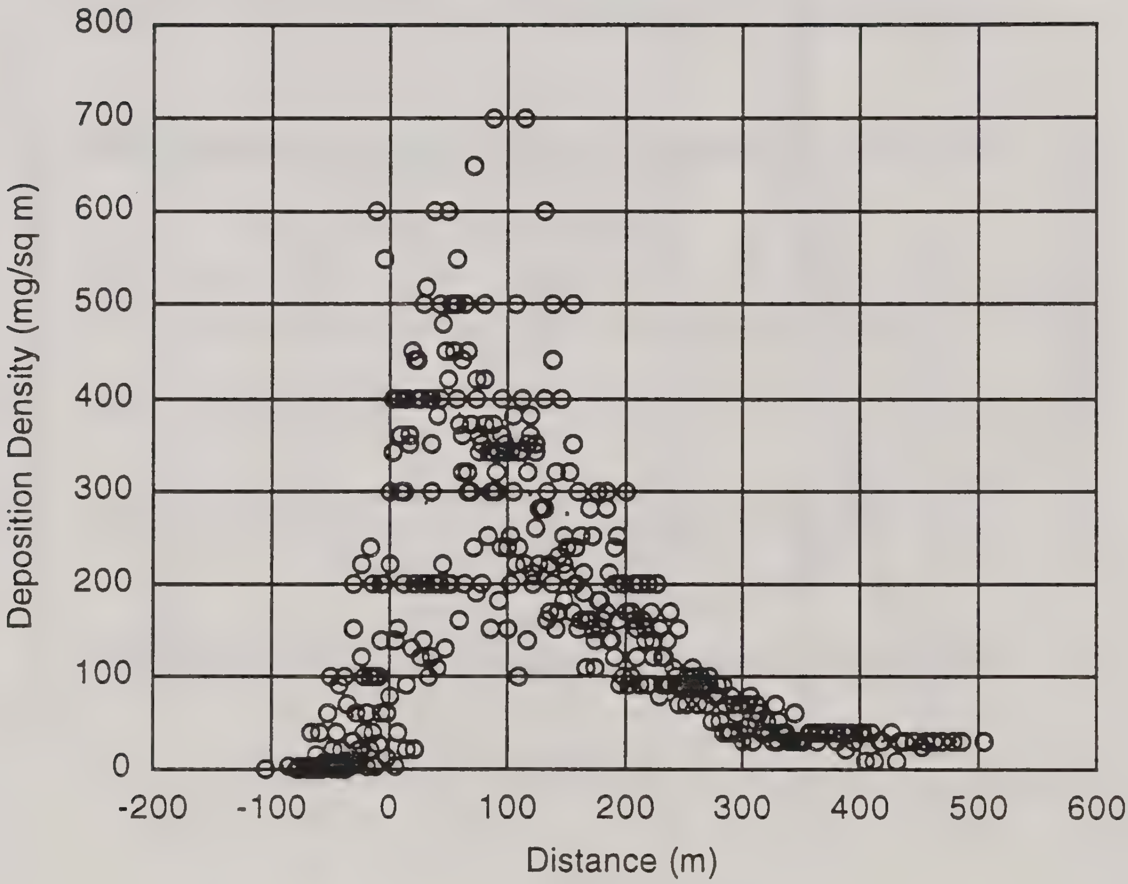


Figure 14: Deposition Data for Trial FS2

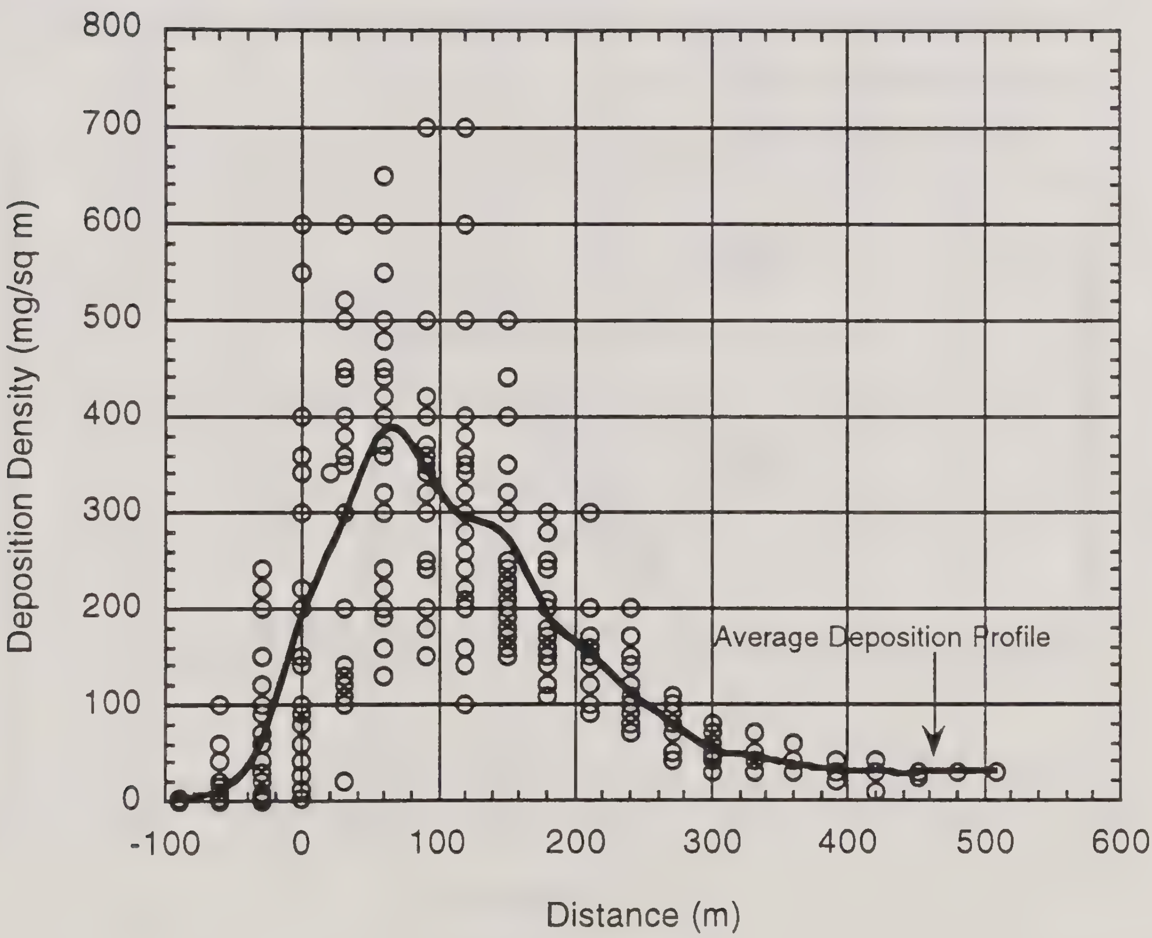


Figure 15: Average Deposition Profile for Trial FS2 (Smoothed)

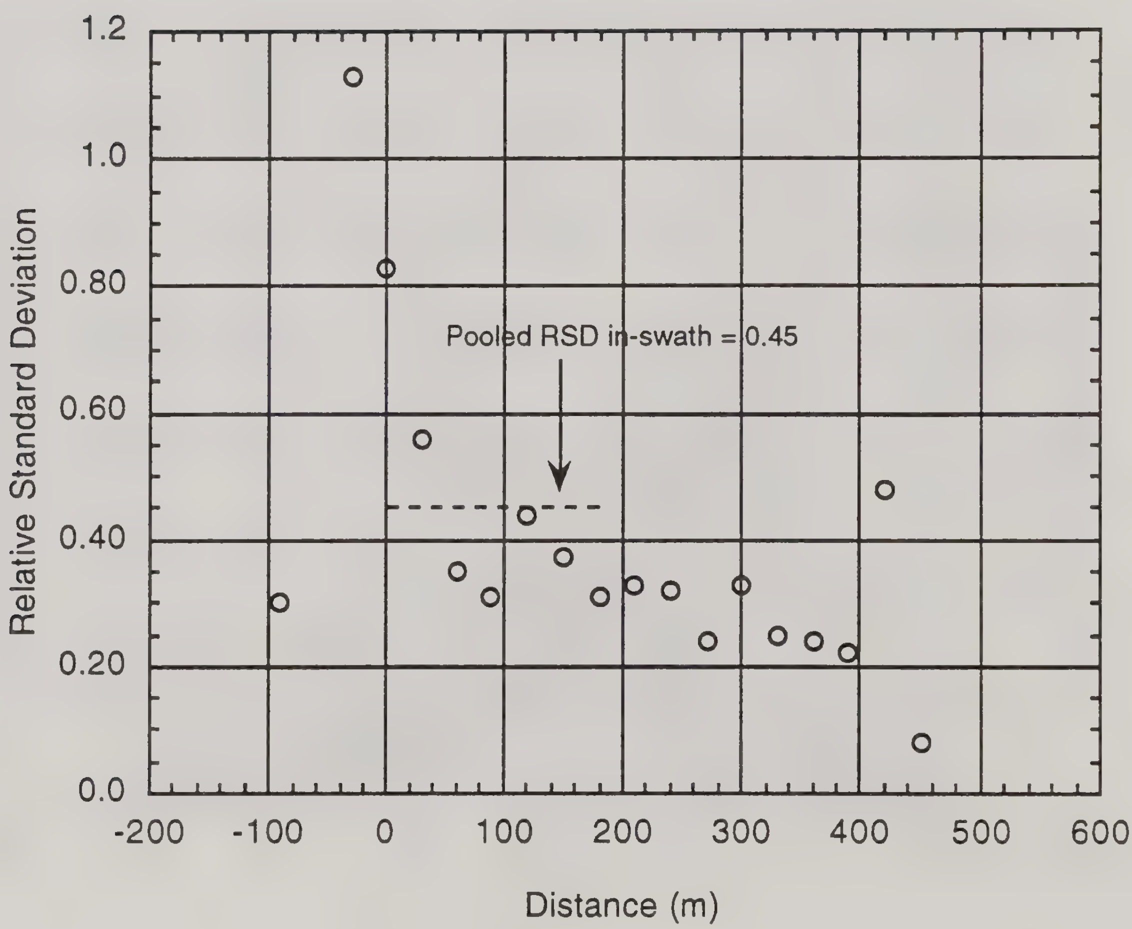


Figure 16: Relative Standard Deviation of Deposition for Trial FS2

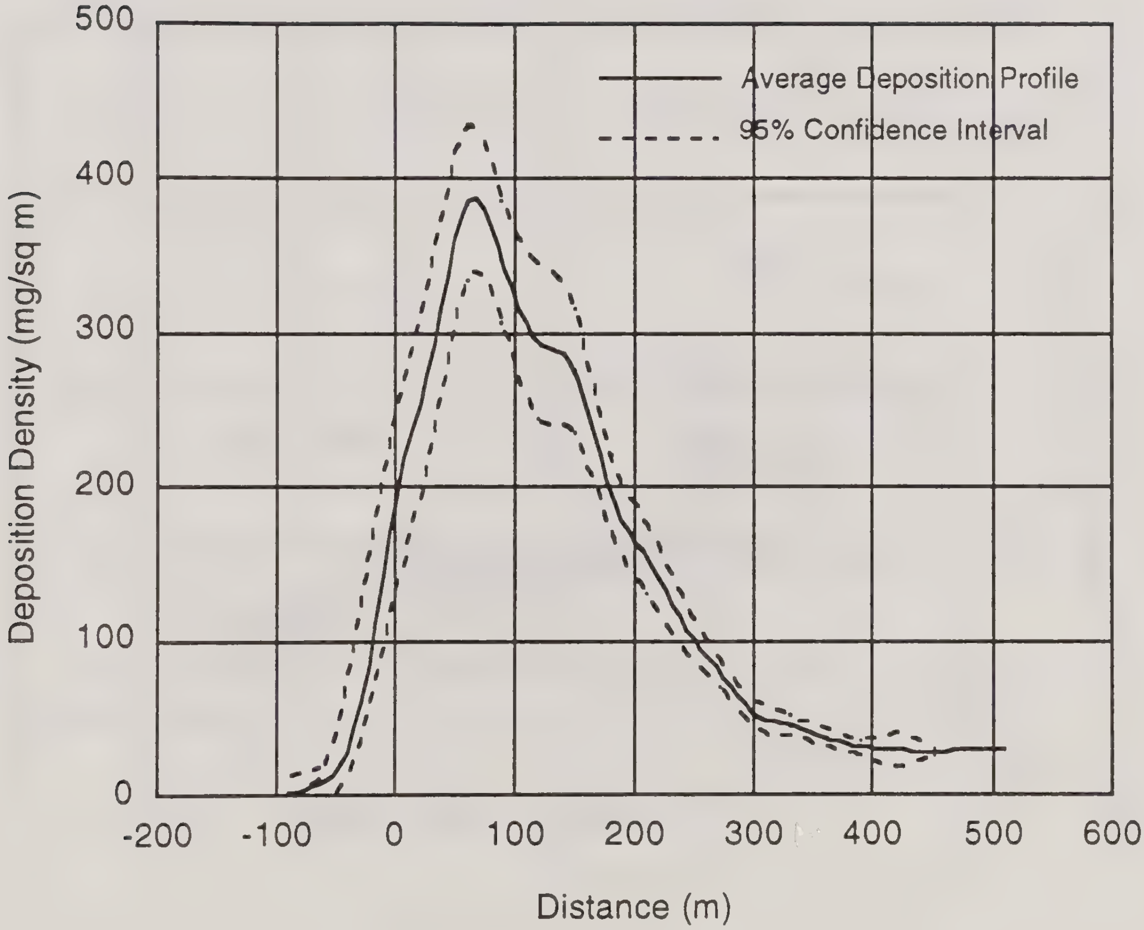


Figure 17: 95% Confidence Interval Bracketing the Average Deposition Profile for FS2

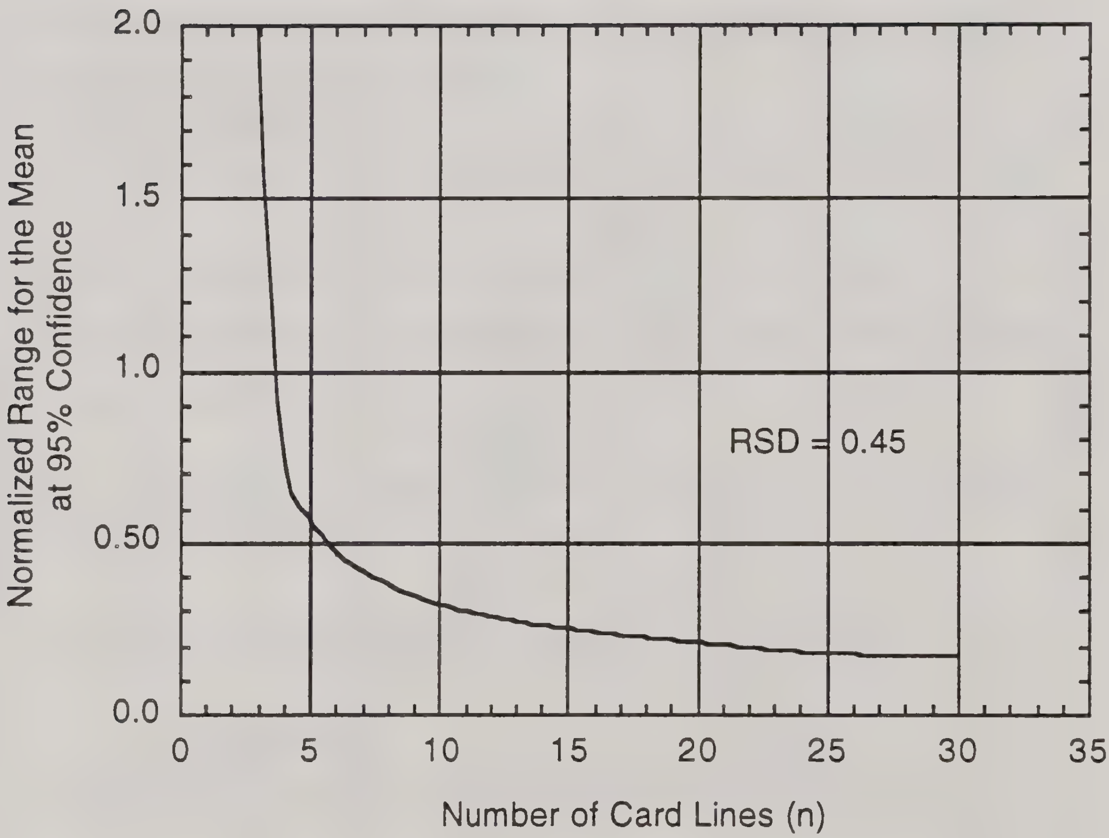


Figure 18: Normalized Range for the Mean Deposition at 95% Confidence, for RSD = 0.45 , FS2

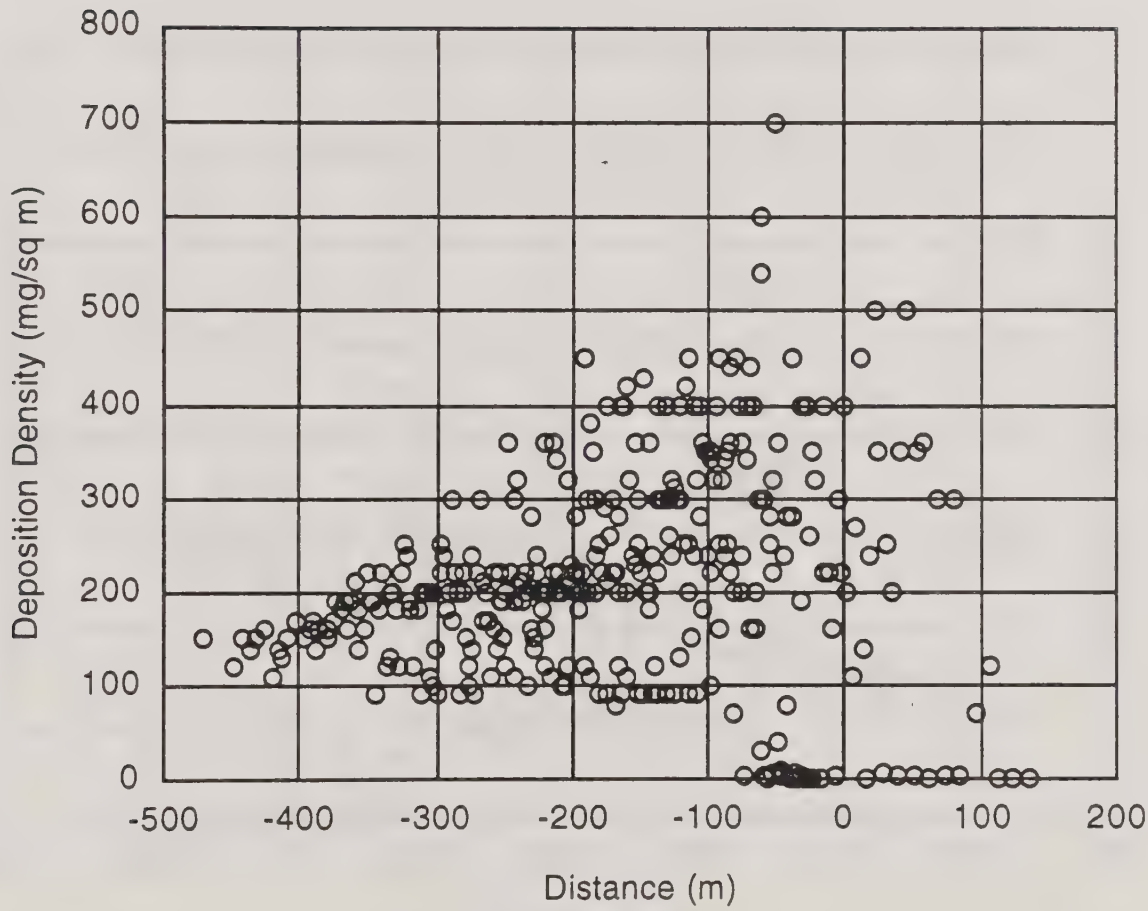


Figure 19: Deposition Data for Trial FS3

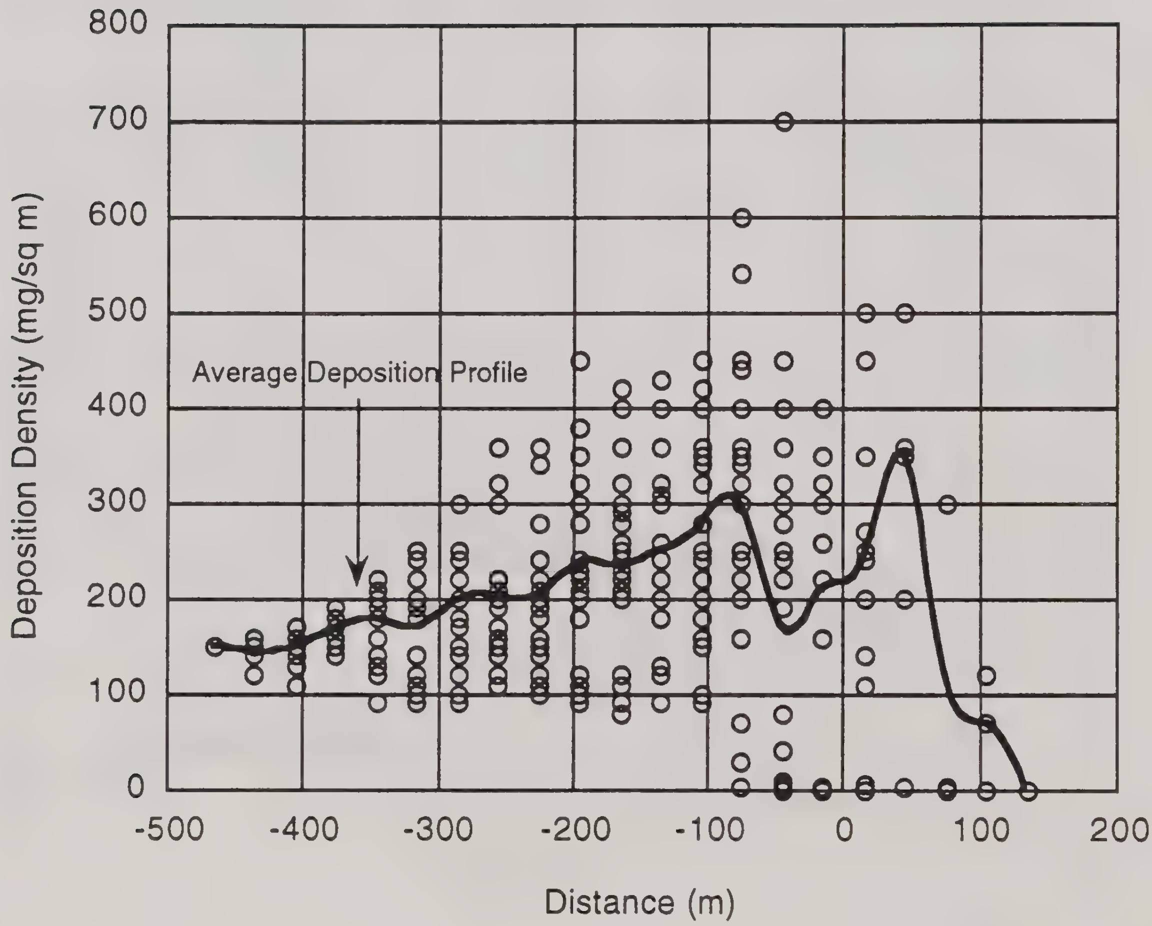


Figure 20: Average Deposition Profile for Trial FS3 (Smoothed)

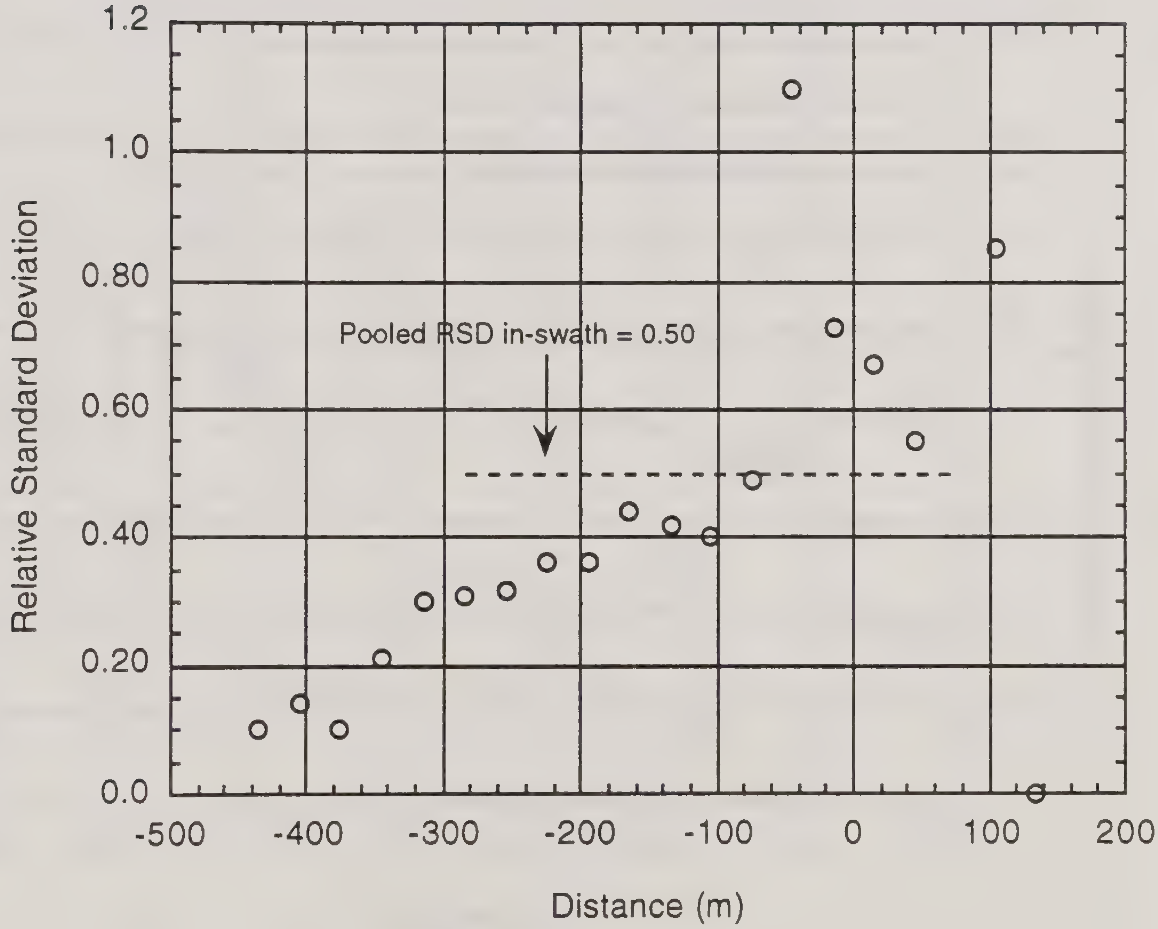


Figure 21: Relative Standard Deviation of Deposition for Trial FS3

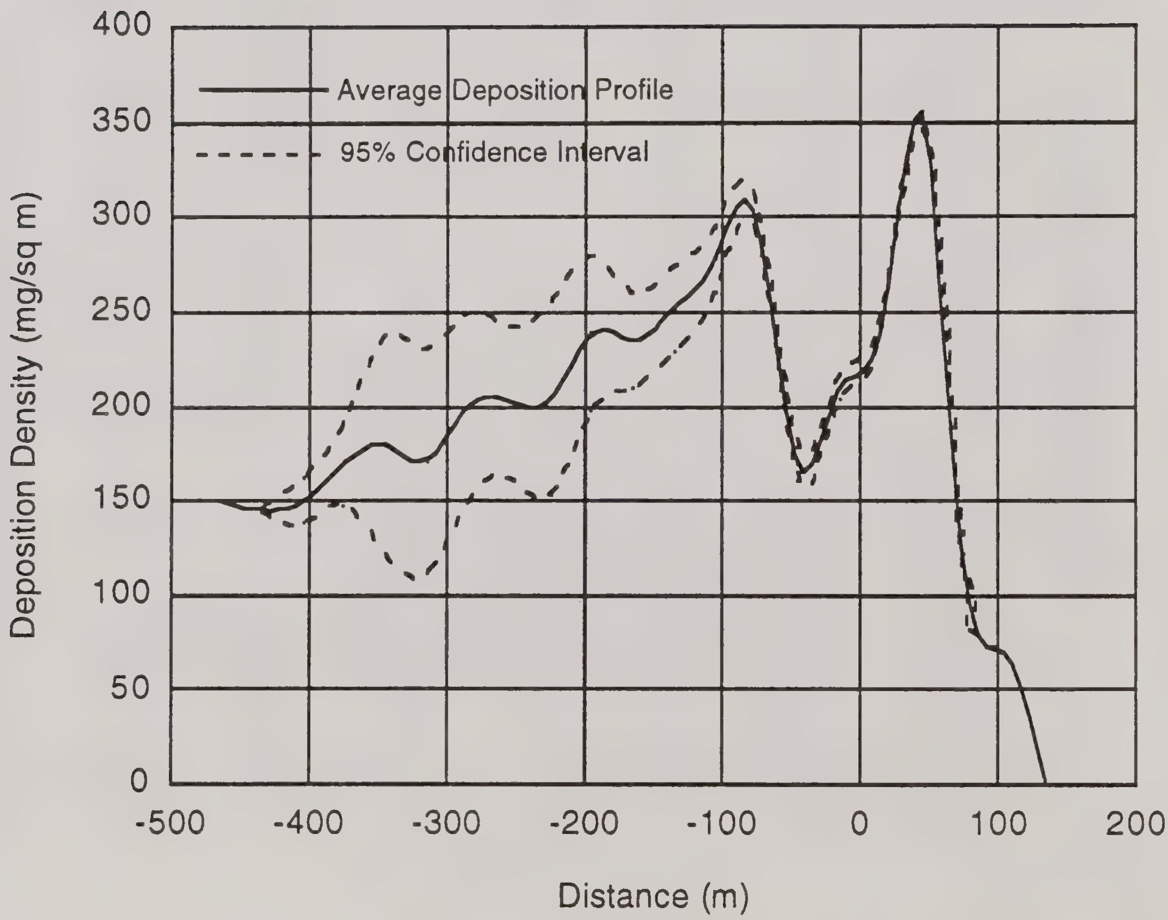


Figure 22: 95% Confidence Interval Bracketing the Average Deposition Profile for FS3

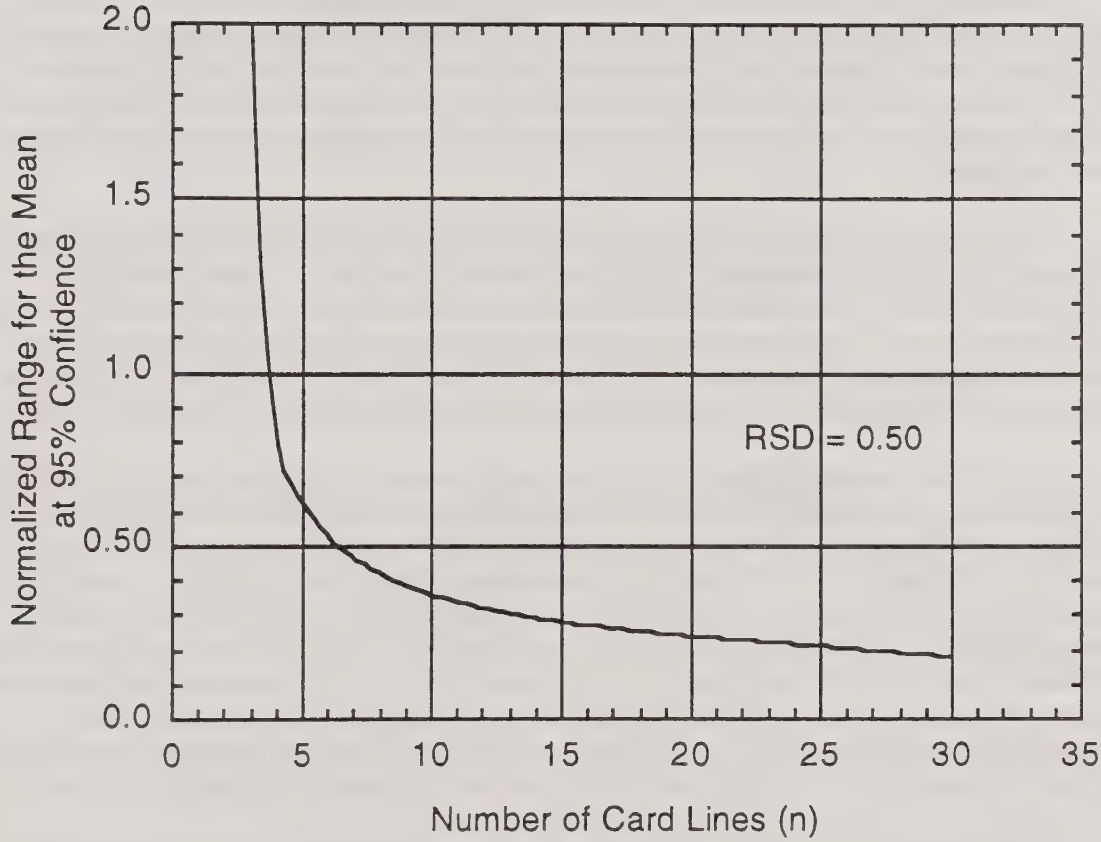


Figure 23: Normalized Range for the Mean Deposition at 95% Confidence, for RSD = 0.50 , FS3

4. Conclusions

As noted, assigning some level of statistical certainty to test data is particularly useful when comparing mathematical simulations of deposition for given test conditions to actual field test data. The level of statistical confidence in the deposition data recovered after field testing can be improved by addressing the sources of experimental error in the test, and also by improving the precision of the estimate of deposition generated from the test data.

An analysis of data from the 1972 MISS test demonstrates the need for clearly defining the test procedure, in other words: exactly describing measurement techniques; spray deposit data collection and reduction techniques; and spray and aircraft systems used. There can be no way to assess the accuracy of data measurement if the techniques employed to gather and analyze drop deposition from the sample cards are based in part on human judgment.

The deposition measured along a card line or over a grid is also affected by test conditions. For example, meteorological data indicate that trial FS2 was nearly a crosswind trial (with a 39 degree difference in wind direction and aircraft heading), while trial FS1 was inwind. Both deposition patterns appear to be the result of winds that are somewhat different than those recorded; if so, the error could be the result of instrument accuracy or of a change in test conditions over the grid (repeatability of test conditions).

Even if the deposition data is collected and measured with great precision and the accuracy of instruments used to measure test conditions is well-established, variable test conditions over the grid could still be a significant source of error when considering deposition over many cards. Maintaining constant spraying conditions (e.g., aircraft height and spray system flow rate) and stable meteorological conditions over the test grid are aspects of this type of error. The data available from the 1972 MISS test are not sufficient to evaluate repeatability of test conditions: to determine this, it is necessary to have more than one spray pass or trial at "identical" conditions (this issue is addressed in the recommendations section and in the Appendix). However, another aspect of experimental error can be evaluated, that of repeatability of the data measured from sampler cards.

The analysis performed here addresses the repeatability of the deposition data measurement at specific parallel distances from the aircraft flight line. This error is indicated by differences in measured deposition from card line to card line, and is due to differences in the assessment of drop deposits from card sampler to card sampler.

Because the 1972 MISS test was flown over a grid, multiple card lines of data are available for each of the three trials studied. An average deposition profile generated from these card lines has multiple samples of deposition data at given points from the aircraft flight line. It has been shown in this report that a level of statistical confidence can be established for such a deposition profile. The minimum number of deposition samples necessary for a "good" estimate of the mean deposition (according to the analysis described previously) is three for inwind trials and four for crosswind trials.

A deposition profile can be defined with only one card line and one trial, assuming an homogenous cloud (the limitations of such an assumption are discussed in MacNichol and Teske, 1994b). If measurement error for the cards along the line is known, there is no need for multiple card lines in order to assess this aspect of the experimental error. If multiple trials are conducted at the same test conditions over this single card line, the issue

of repeatability of test conditions will also have been addressed. In either case, there can be some degree of certainty assigned to the data from the test because the precision of the test data can be determined (either from the known card measurement error or from the error due to variation in test conditions). However, if nothing is known about the repeatability of the test conditions or the data measurement, no level of statistical certainty can be assigned to the data.

5. Recommendations

The following recommendations are made with regard to planning and designing field trials to characterize spray patterns from aircraft. The recommendations address the issue of establishing a degree of statistical certainty in the ground deposition profile generated from aerial spray field tests. Statistical analysis of field test spray patterns, in particular establishing a confidence interval for the spray pattern, is desired in order to better compare mathematical simulations (such as those generated with FSCBG) to actual deposition data.

1. The accuracy of all measurement techniques (in particular instrument accuracy) should be assessed whenever possible.

2. The procedure for assessing spray deposits on ground cards should also be clearly outlined, particularly the method of assessment and the time elapsed before the cards are read. Data reduction techniques used to generate test results should also be defined (including the spread factor expression used to convert stain size to drop size).

3. Spray system variables such as aircraft speed and height over the test area should be measured at multiple points during a spray pass to ensure that test conditions reported are a true representation of the actual spray pass.

4. The repeatability of test conditions over the grid can represent a significant source of error. More than one spray pass at nearly identical test conditions is recommended whenever possible. Although it would be impossible to identically duplicate meteorological conditions for multiple passes, the variation of meteorology over the grid during each pass would indicate the precision of the meteorological measurements made.

5. Card measurement error consists of: inaccuracies in the collection of data and in data reduction techniques; and variability of deposition data at a specific distance from the aircraft flight line (the subject of the statistical analysis performed here). Assuming an homogenous cloud, and assuming that the total card measurement error is known, the field test data gathered from one card line can be used to characterize the ground deposition profile with a clearly defined statistical certainty. However, if the card measurement error is not known, at least three, preferably four, sampling positions (card lines) should be used to characterize the ground deposition from a spray pass in order to assign a degree of certainty to the profile generated. Multiple samples of deposition data need not be available over an entire card line. Provided that the accuracy of the testing process is well defined and that the precision of test conditions has been addressed, placing extra sampling positions parallel to selected stations along a primary card line would be sufficient to assess a statistical level of confidence in the field test data.

6. A field test is recommended in order to assess the relative importance of the aspects of experimental error discussed above, employing all of the recommendations made so far. A test design is described in the Appendix.

6. Acknowledgment

The author would like to graciously acknowledge the support of John W. Barry, Project Officer, USDA Forest Service, Forest Pest Management (Davis, CA). The 1972 MISS trials were made possible through the cooperative effort of US Army Deseret Test Center personnel and USDA Forest Service personnel at Missoula Equipment Development Center (Missoula, MT), Region I Forest Insect and Disease Branch (Missoula, MT) and the Pacific Southwest Forest and Range Experiment Station (Berkeley, CA).

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Appendix: Proposed Test Design

The suggested field test to assess different aspects of experimental error in aerial spray trials should consist of the following:

1. A single card line should be laid down in the test area, with multiple parallel sampling stations placed at several points along the line (Figure A1). The extra sampling stations should be placed at points in-swath as well as out-of-swath.

2. Meteorological data should be read at several locations in the test area (at least two, preferably three).

3. Flight conditions should be recorded at several points during the spray pass, particularly aircraft release height.

4. Multiple passes over the test area should be made at the same test conditions (with meteorological conditions as close as possible to previous test conditions).

5. A separate set of sample cards spiked with a known amount of the spray formulation should be included in the trial. This set of cards will allow the accuracy of the data measurement technique to be assessed.

6. Sample cards should be collected promptly following the test and interpreted using the ASCAS coupled with card-reading software (Sanderson, 1991), or a similar technique.

7. The accuracy of spray system variables (such as the spray flow rate measured) should be evaluated.

8. Instrument accuracy (including instruments used to record meteorology as well as flight instruments) should be evaluated.

The statistical results from this test will help quantify all of the open items discussed in this report.

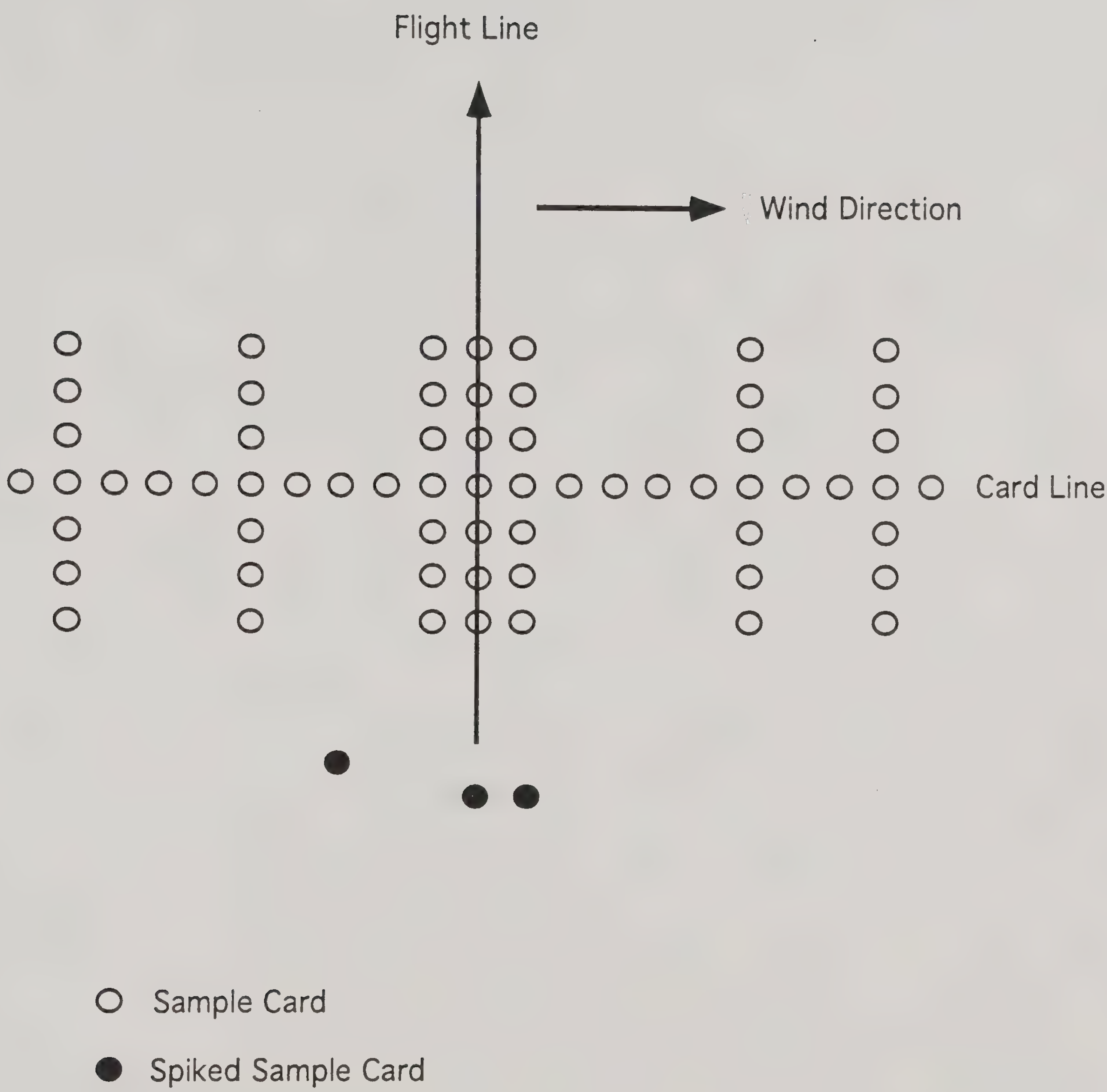

Figure A1: Placement of Sample Cards and Orientation of Wind and Aircraft Flight Line for the Recommended Test.

United States
Department of
Agriculture

Forest Service

Forest Pest
Management

Davis, CA

C-47 Aircraft Spray Deposition

Part 2:

FSCBG Model Prediction of Deposition and Biological Response

FPM 95-8
April 1995

Pesticides used improperly can be injurious to human beings, animals, and plants. Follow the directions and heed all precautions on labels. Store pesticides in original containers under lock and key—out of the reach of children and animals—and away from food and feed.

Apply pesticides so that they do not endanger humans, livestock, crops, beneficial insects, fish, and wildlife. Do not apply pesticides where there is danger of drift when honey bees or other pollinating insects are visiting plants, or in ways that may contaminate water or leave illegal residues.

Avoid prolonged inhalation of pesticide sprays or dusts; wear protective clothing and equipment, if specified on the label.

If your hands become contaminated with a pesticide, do not eat or drink until you have washed. In case a pesticide is swallowed or gets in the eyes, follow the first aid treatment given on the label, and get prompt medical attention. If a pesticide is spilled on your skin or clothing, remove clothing immediately and wash skin thoroughly.

NOTE: Some States have restrictions on the use of certain pesticides. Check your State and local regulations. Also, because registrations of pesticides are under constant review by the U.S Environmental Protection Agency, consult your local forest pathologist, county agriculture agent, or State extension specialist to be sure the intended use is still registered.

FPM 95-8
C. D. I. Technical Note No. 95-04
April 1995

C-47 AIRCRAFT SPRAY DEPOSITION

PART 2:

FSCBG MODEL PREDICTION OF DEPOSITION AND BIOLOGICAL RESPONSE

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Project Officer

Summary

An aerial spray field test conducted by the USDA Forest Service in cooperation with the U.S. Army Deseret Test Center in 1972 provides six sets of multiple-spray deposit card line data, three of which include data to determine dose/response. A C-47 USDA Forest Service aircraft applied the chemical insecticide Zectran® over receptors of Printflex detector cards and petri dishes containing target insect larvae. The six trials were conducted over the horizontal grid at the U.S. Army Dugway Proving Ground, Utah. In Part 1 of this three-part report, a statistical analysis was performed on ground deposition data from the first three trials. In the present study (Part 2), FSCBG simulations of ground deposition are presented for the six trials, and dose/response is predicted where applicable. Average correlation of FSCBG predictions to the field data is R^2=0.61. Dose/response data available from the field test consisted of insect mortality counts for three of the trials. These mortality rates were used to determine effective swath widths for each of the trials; the effective swath width was that distance in which there would be 100% insect mortality within 24 hours after application. Predicted effective swath widths for four of the trials are within 15% of the values indicated by field test data. Expected dose/response is within 5% of the observed levels for the three trials for which insect mortality rate was measured.

Table of Contents

List of Figures

List of Tables

1. Introduction

In the spring of 1972, the USDA Forest Service (FS) and U.S. Army Deseret Test Center conducted a cooperative test to obtain aerial spray data on the U.S. Air Force (USAF) PWU-5/A Modular Internal Spray System (MISS) (Taylor et al., 1972). As previously described in MacNichol and Teske (1994b), the MISS system was developed in response to USAF Special Operations Force requirements, which included the capability for aerial application of pesticides for insect and vegetation control. It was an airborne, modular, reusable, high capacity spray system with wing booms and fuselage spray stations.

The test is described in detail by Taylor et al. (1972). The MISS was installed on a C-47 aircraft and tested with a formulation of the insecticide Zectran®. In order to evaluate system effectiveness, and to satisfy licensing requirements for the Zectran® formulation, a FS spray system installed on a C-47 was included in the test as a baseline system. The C-47 is the military version of the DC-3.

The test consisted of seven trials, six at the U.S. Army Dugway Proving Ground (DPG) in Utah and one at Lolo National Forest in Montana. The DPG trials evaluated the FS spray system and the MISS spray system over open and flat desert terrain; three trials were conducted using the baseline FS system and three trials were conducted using the MISS. The trial at Lolo National Forest was an operational demonstration of the MISS over forested terrain.

All six of the trials conducted at DPG (three using the baseline FS spray system and three using the MISS) were conducted over a 0.8 km x 0.8 km horizontal grid with sampling positions throughout the grid. Thus, ground deposition data from these trials can be organized into many lines of deposition (or sample card lines) normal to the aircraft flight path. Deposition from trials FS1, FS2 and FS5 can be represented by 25 card lines, FS3 by 16 card lines, FS4 by 17 card lines and FS6 by 18 card lines. A predicted deposition profile generated using the Forest Service Cramer-Barry-Grim FSCBG model 4.3 (Teske et al. 1993) can thus be compared to the field test data.

This report and a companion report which describes a statistical analysis of the first three trials in this test (MacNichol and Teske 1994b) are the first detailed analyses of the 1972 MISS test in the 22 years since it was conducted. The test is unique for several reasons: never has there been another opportunity to fly an aircraft over such a densely sampled grid array to look at the "footprint" of a spray pattern; never have there been so many samples; and, this aerial spray field test is the only known test conducted in which live insects were placed on the grid with deposition samples in order to look at the dose/response.

Part 1 of this report (MacNichol and Teske 1994b) examined the statistics of the multiple card line samples and made recommendations with regard to establishing a level of statistical confidence in field test results. Statistical analysis of field test spray patterns, in particular establishing a confidence interval for the spray pattern, was discussed as a means of better comparing mathematical simulations (such as those generated with FSCBG) to actual deposition data. These results were consistent with other studies we have undertaken to interpret variations in field test results (Teske 1992; Teske, Barry and Ghent 1994).

The present report compares dose/response levels predicted using FSCBG to the actual field test data. The abundance of deposition data available from the 1972 MISS test makes this paper a natural extension to the ongoing FSCBG validation effort (MacNichol and Teske 1993a, 1993b, 1994a, 1994c).

2. Field Trials Summary

2.1 Test Scope

The MISS test consisted of seven trials, six conducted at DPG, Utah and one in the Lolo National Forest, Montana. Four test phases, designated A through D, were conducted from late April through late June 1972. Table 1 summarizes the location, date and requirements for each test phase.

This report will use data generated during phases A, B and C (trials FS1 through FS6). Phase A was conducted at DPG with the FS spray system on a C-47 aircraft and took place on April 27, 1972. Phases B and C were conducted at DPG on June 24 and 25, 1972. The trials in these phases were conducted with the MISS system on a C-47.

2.2 Spray Site

The trials of interest were conducted on the Horizontal Grid at DPG, Utah. There were 49 rows and 40 lines of horizontal sampling positions, all at ground level, spaced at 15.2 meter intervals. The portions of the grid used in each trial varied as shown in Figures 1 through 6.

In trials FS1, FS2, FS3 and FS6, Printflex card samplers were placed at every other grid sampling position, for a total of 625 sampling stations over the grid. Printflex is a paper that is somewhat more absorbent than Kromekote paper (Teske, MacNichol and Barry 1995). The distance between sampling stations was 30.4 meters. Trial FS3 also had 141 special sampling stations with coated glass slides and spruce budworm larvae (SBWL) in petri dishes. Data from these special sampling positions were used to evaluate the effectiveness of Zectran® application and to indicate sampling density for later trials. These biological data provide a rare opportunity to look at model deposition patterns as a function of both card deposition and biological effectiveness.

In trials FS4 and FS5 (Phase B), less than 600 sampling stations were used. The test officer selected the portion of the grid used based on prevailing meteorological conditions. This phase of the test was conducted to provide a qualitative assessment of the dissemination characteristics of the MISS system spraying Zectran®.

2.3 Meteorological Measurements

A 48-meter profile mast located in the vicinity of the target array (Taylor et al. 1972) was instrumented to measure: wind speed at 0.5, 1, 2, 4, 8, 16, 30, and 45.7 meters above ground; wind direction at 2, 16, 32, and 48 meters above ground; temperature at 1 meter above ground; and temperature gradient between 0.5 meter and 1, 2, 4, 8, 16 and 32 meters above ground level.

Two-meter masts were located at each corner of the grid array to measure wind speed and direction (these four masts are indicated on Figures 1 through 6).

Surface observations of dry and wet bulb temperature and cloud cover were taken 1500 meters northeast of the grid center, and pilot balloon (PIBAL) observations were taken at the same location (Taylor et al. 1972).

Table 2 summarizes the meteorological data available for trials of interest here. Note that meteorological data for phases B and C are incomplete, in particular for trial FS4. Where actual field data were unavailable, values were estimated based on time of day, probable flight path over the grid and suggested values given by Taylor et al. (1972).

Two of the trials were conducted in the early morning, and one (FS3) in the early evening. For the Phase A trials, weather conditions remained similar throughout the day, with relative humidity at 28 to 29 percent and temperature between 6 and 11 degrees Celsius.

Wind speed data are available at 2 meters and at 48 meters, from 1.5 to 2.2 m/sec; wind speed readings are similar at both heights for each of the trials. Wind direction is only available at 2 meters and varied considerably over the six trials. Note that, while trials FS1 and FS2 were both intended to be inwind trials (Taylor et al. 1972), trial FS2 was flown with a 39 degree difference in wind direction and aircraft heading. Thus, FS2 is nearly a crosswind trial. Trial FS3, intended to be a crosswind trial, was flown with a 68 degree difference in wind direction and aircraft heading, making it almost an inwind trial. Wind direction and aircraft flight path for trials FS5 and FS6 were estimated based on the ground deposition pattern.

2.4 Spray Aircraft Configuration

A C-47 cargo aircraft was equipped with a FS spray system for the phase A trials and with the MISS system for the phase B and C trials (Taylor et al. 1972). Table 3 summarizes the known aircraft and spray system characteristics.

Aircraft altitude above ground (spray release height) for the trials varied from 53 to 100 meters, as shown in Table 2. Aircraft spraying speed varied from 59.1 to 66.8 m/sec (115 -129 kts) for all three trials. Aircraft heading is also shown in Table 2. As previously mentioned, aircraft heading and wind direction coincide in FS1 but not in the other five trials. Aircraft position over the grid can be seen in Figures 1 through 6. The aircraft flew over the center of the grid in all of the trials except FS5 and FS6.

Spray material was released at the rate of 150 gal/min for 1 minute, starting 805 meters upwind of the grid. The spray material is described in detail by Taylor et al. (1972). The Zectran® FS-15 solution consisted of 24 ounces of Zectran® (4-dimethylamino-3, 5-xylyl methyl carbamate) in solution with one gallon of tri-propylene-monomethyl glycol ether (TPM). The spray material was a mixture of Zectran® FS-15 and either fuel oil or kerosene (one gallon of Zectran® FS-15 solution mixed with 9 gallons of either Number 2 Fuel Oil or odorless kerosene), dyed with Oil Red dye, chemical index (CI) 258 at 1.0 percent weight per volume. An estimate of the drop size distribution is shown in Table 4.

2.5 Data Reduction Procedure

Following each trial, the Printflex card samplers were collected, held until droplet stabilization (Taylor et al. 1972), then read. Visual observation and the Automatic Spot

Counting and Sizing System (ASCAS, Young, Luebbe and Barry 1977) were used to recover the droplet spectrum of the ground level deposition pattern. Card samplers from trials FS1, FS2, FS4 and FS5 appear to have been evaluated visually, while card samplers from trials FS3 and FS6 were microfilmed, and sizing and counting were performed by the ASCAS instrument at DPG. Taylor et al. (1972) noted that samplers at or near pattern center could not be processed by ASCAS due to droplet overlap, and that ASCAS estimates lacked definition for the outer areas of the deposition pattern and for areas of heavy deposition. Therefore, these estimates were adjusted to give more realistic results. Unfortunately, the accuracy of these adjustments is unknown.

Ground deposition data generated for trials FS1 through FS6 consist of predominant drop size (in micrometers) and deposition density (in mg/sq m). Contours of ground deposition in trials FS1 through FS6 are shown in Figures 7 through 12. Note that the edges of the contours for all of the trials are uneven, especially so for trials FS2, FS3, FS4 and FS5. Trial FS3 shows pockets of heavy deposition (denoted by letter E in Figure 9) surrounded by areas of lighter deposition. Such a contour pattern suggests turbulent atmospheric conditions, changes in wind direction, aircraft release height variability over the test grid, or spray system performance variability during the test. A similar pattern can be seen in trials FS4 and FS5 (Figures 10 and 11). The amount of variability seen here occurs over relatively flat terrain. The presence of complex forest terrain, typical of most areas sprayed by the Forest Service, could only amplify the variability. Pattern edge effects are discussed in detail in MacNichol and Teske (1995).

Note also that some edges of the grid in trials FS3 through FS6 are in areas of medium to high deposition (for trial FS3, letters C and D in Figure 9), indicating that the entire swath was not captured on the grid.

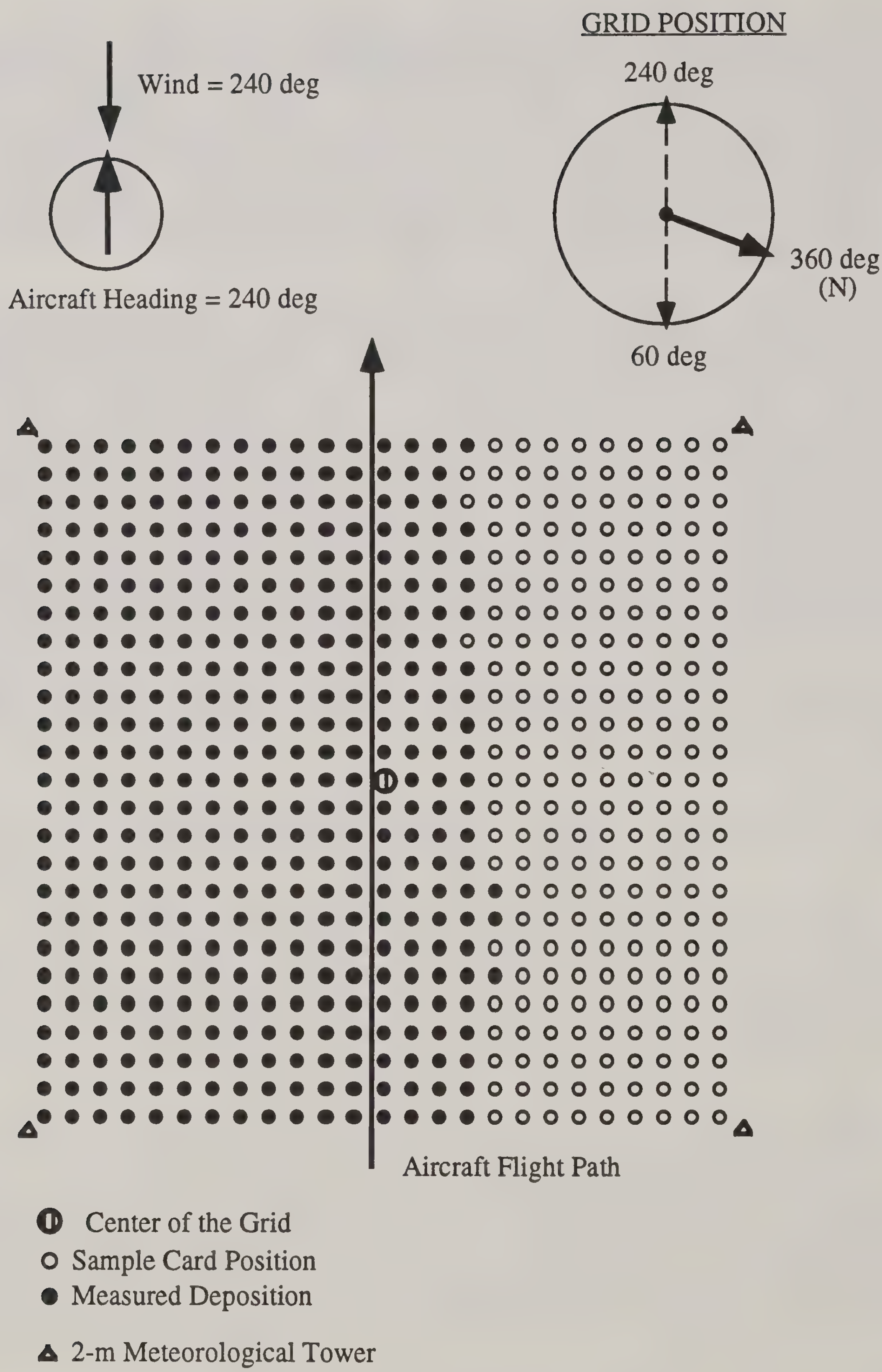


Figure 1: Trial FS1, horizontal grid at U.S. Army Dugway Proving Ground, Utah

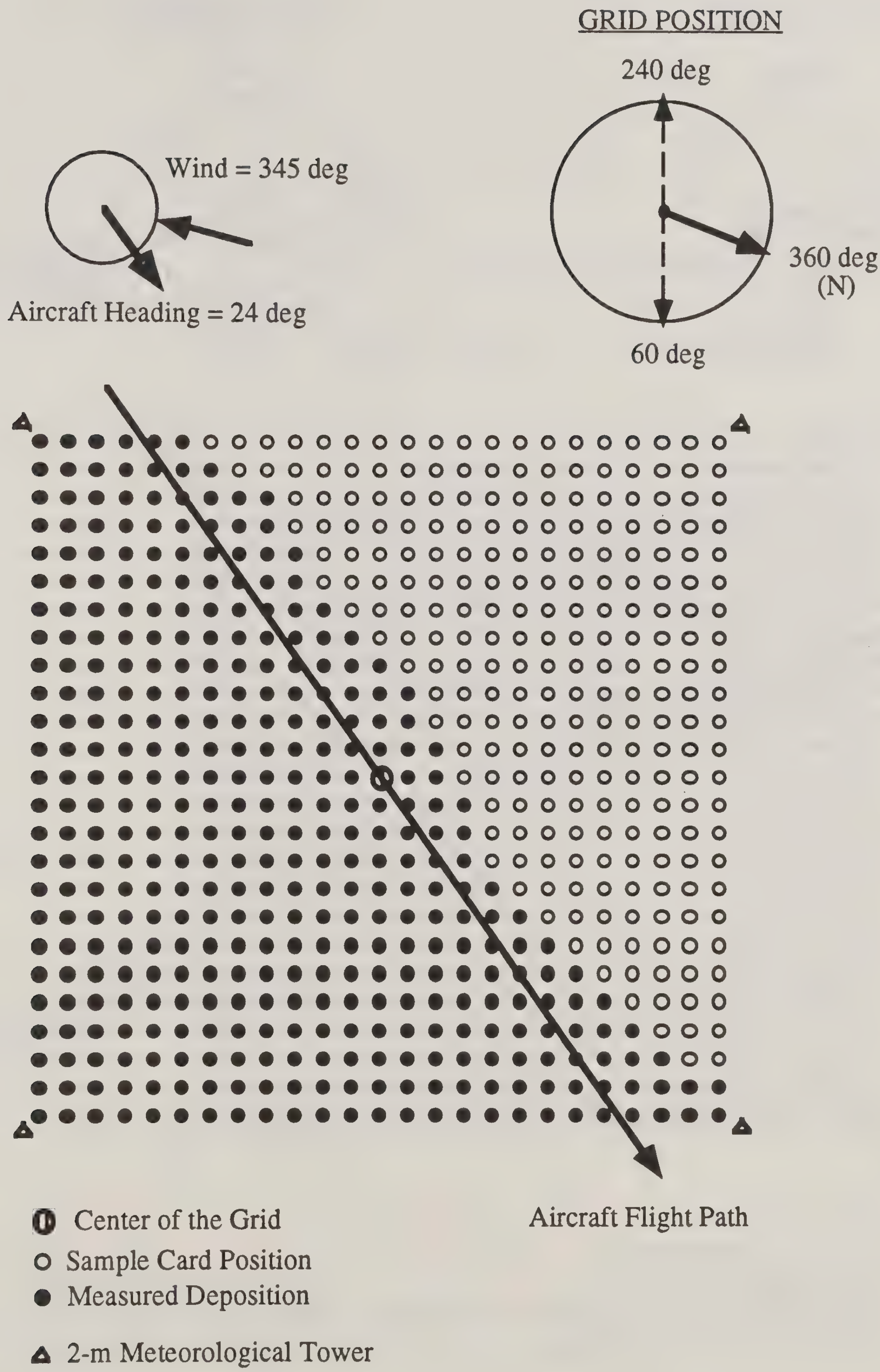


Figure 2: Trial FS2, horizontal grid at U.S. Army Dugway Proving Ground, Utah

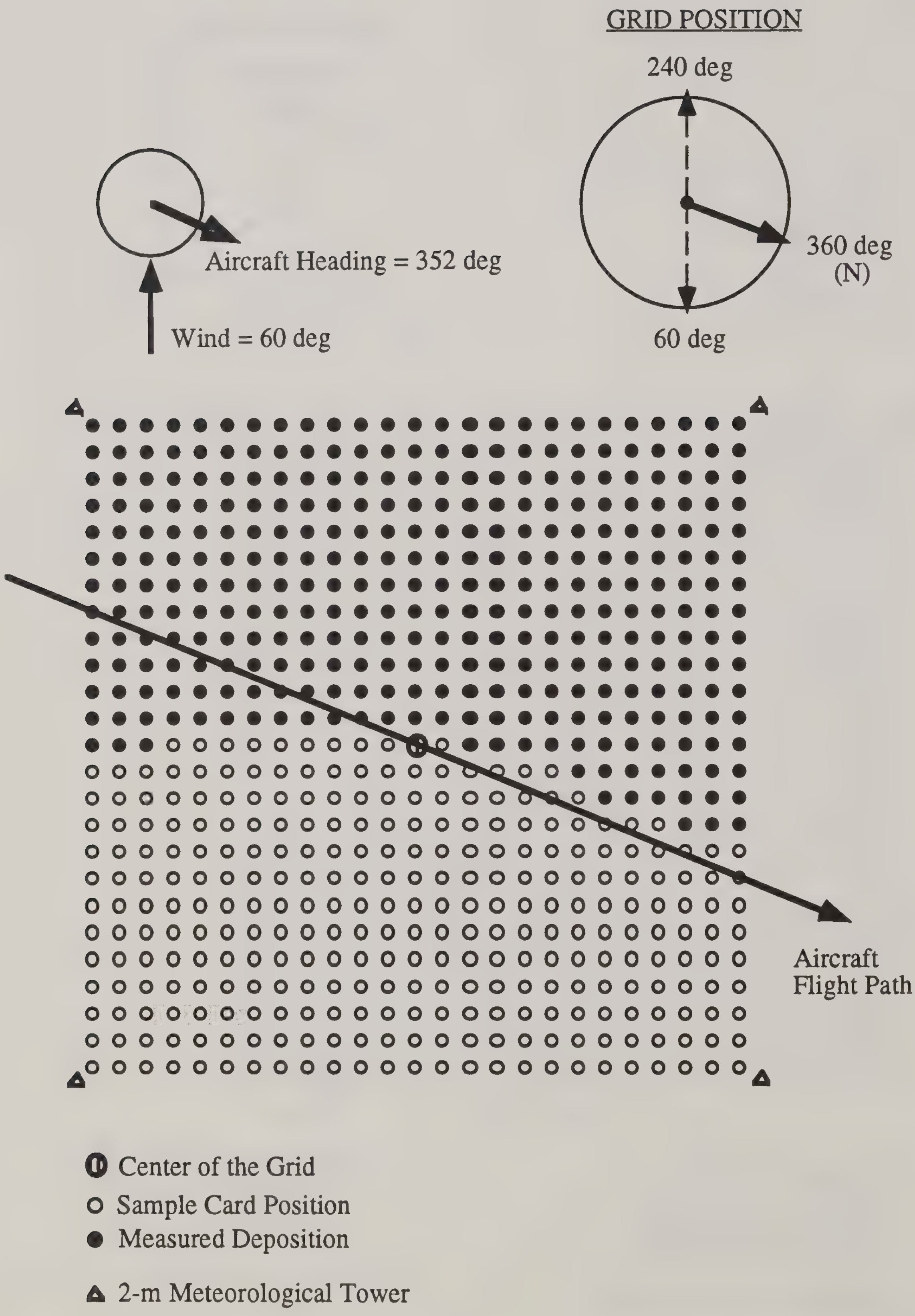


Figure 3: Trial FS3, horizontal grid at U.S. Army Dugway Proving Ground, Utah

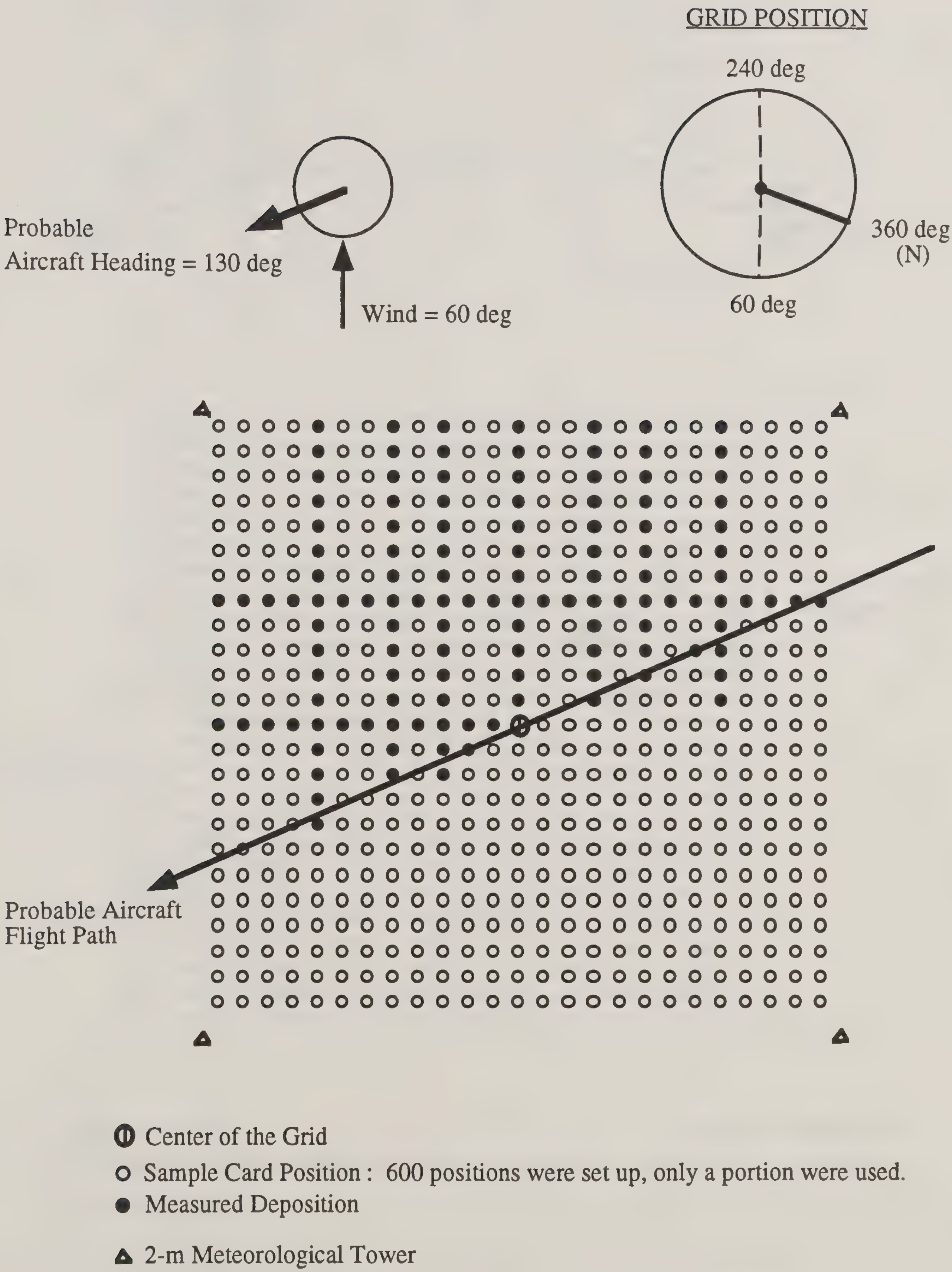


Figure 4: Trial FS4, horizontal grid at U.S. Army Dugway Proving Ground, Utah

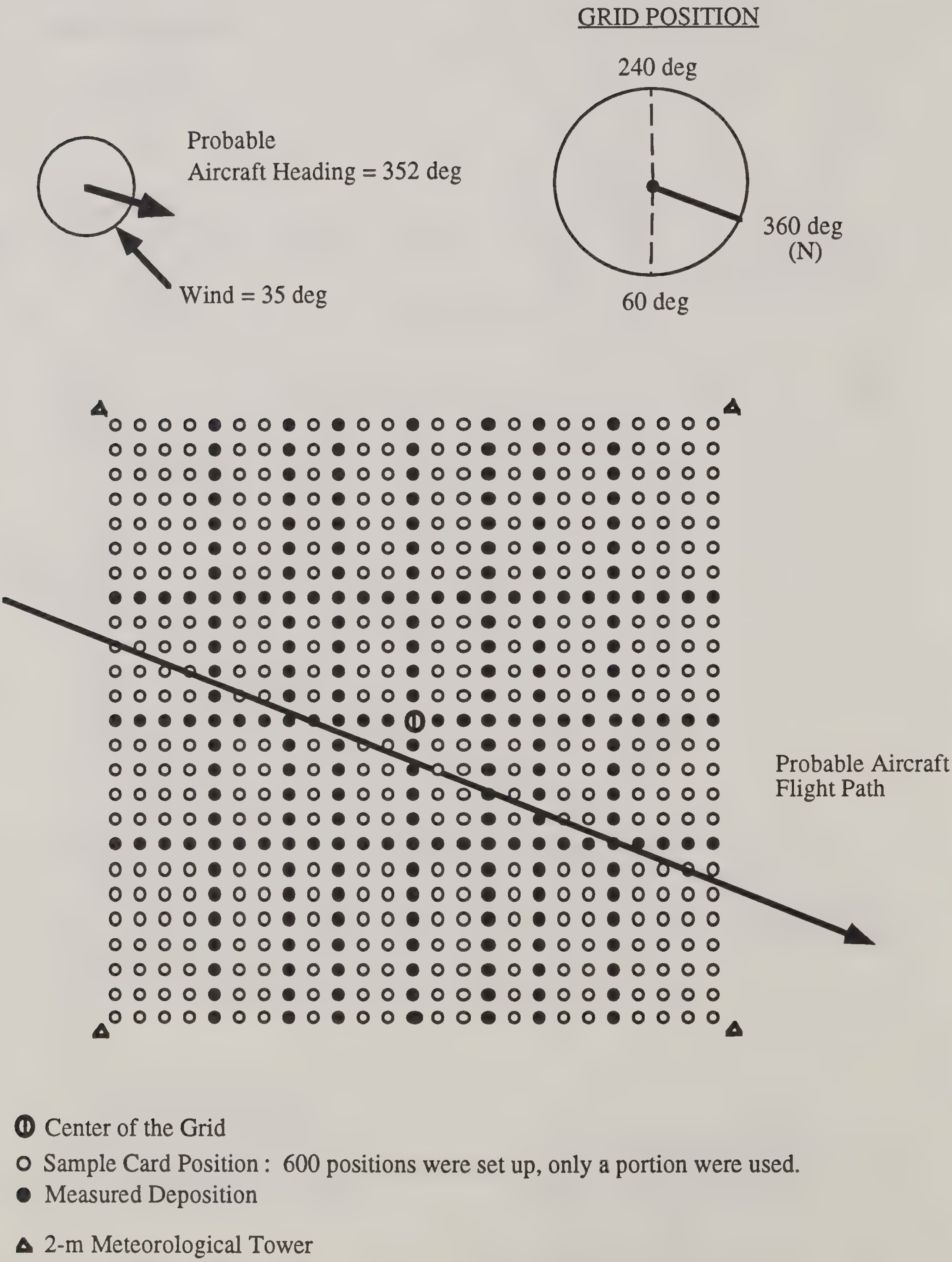


Figure 5: Trial FS5, horizontal grid at U.S. Army Dugway Proving Ground, Utah

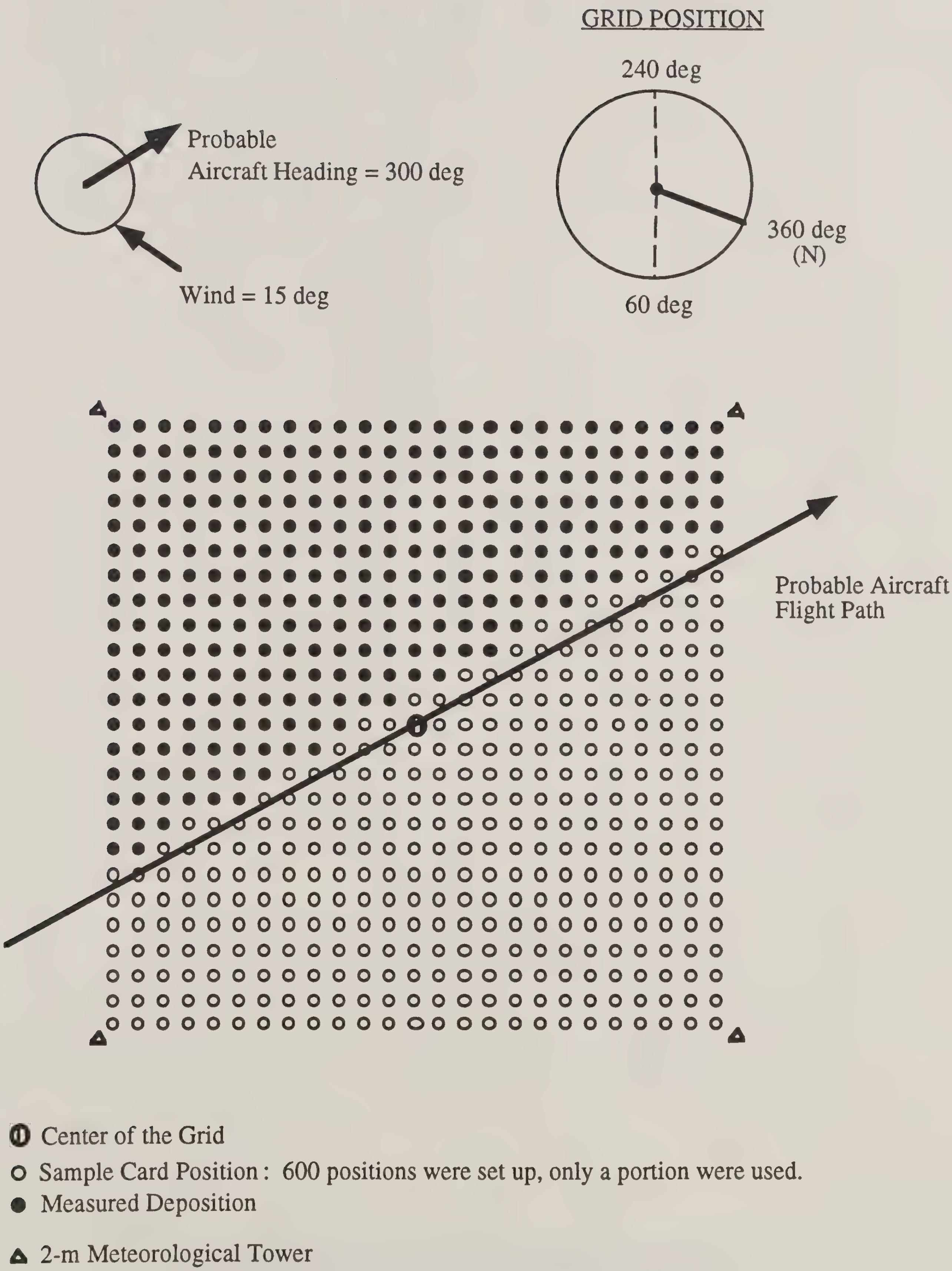
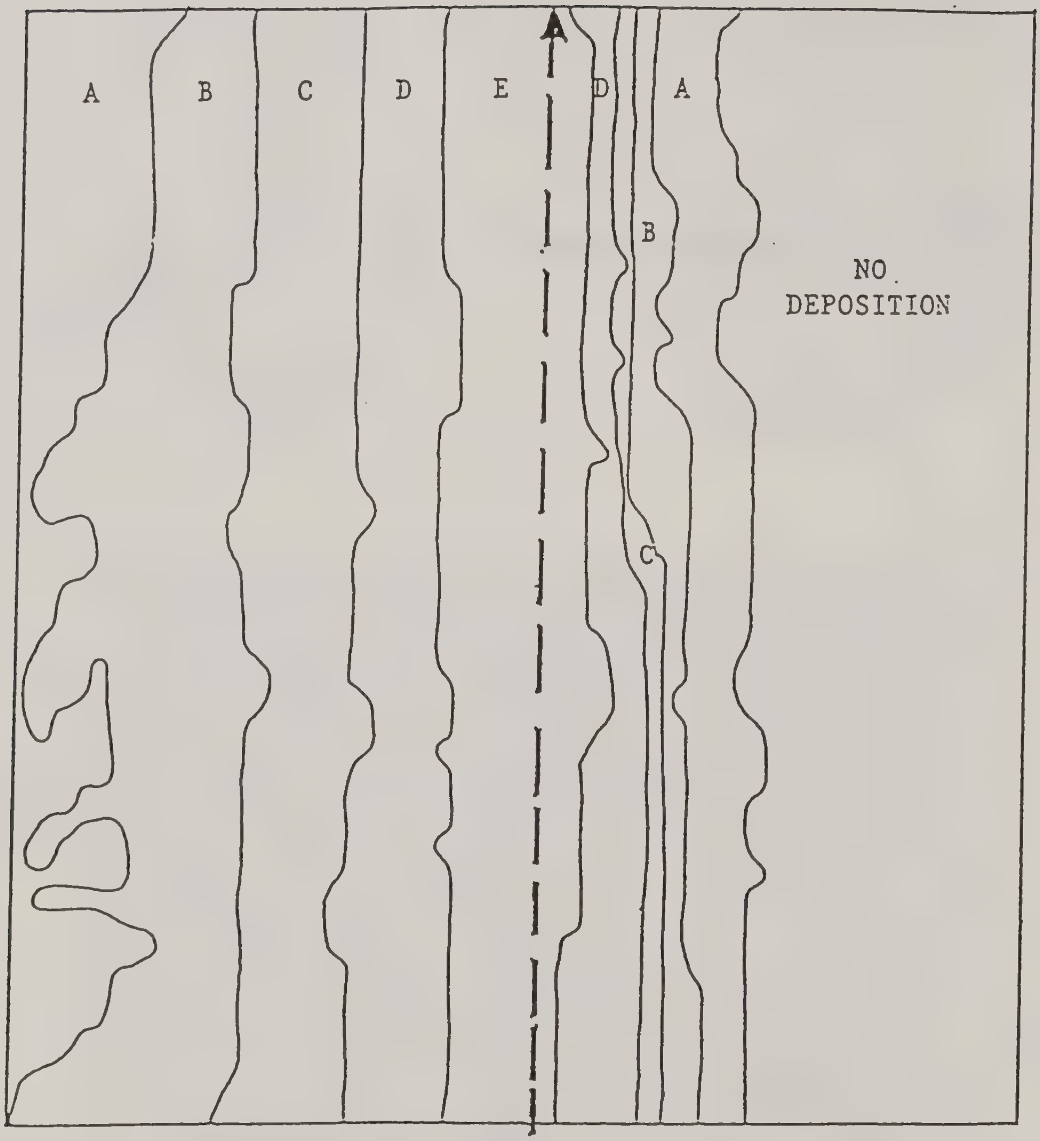


Figure 6: Trial FS6, horizontal grid at U.S. Army Dugway Proving Ground, Utah



FLIGHT LINE

A 1 - 29 mg/sq m Deposition Density
B 30 - 80 mg/sq m " "
C 90 - 170 mg/sq m " "
D 180 - 390 mg/sq m " "
E 400 - 900 mg/sq m " "

Figure 7: Trial FS1 deposition contour
(horizontal grid, U.S. Army Dugway Proving Ground)

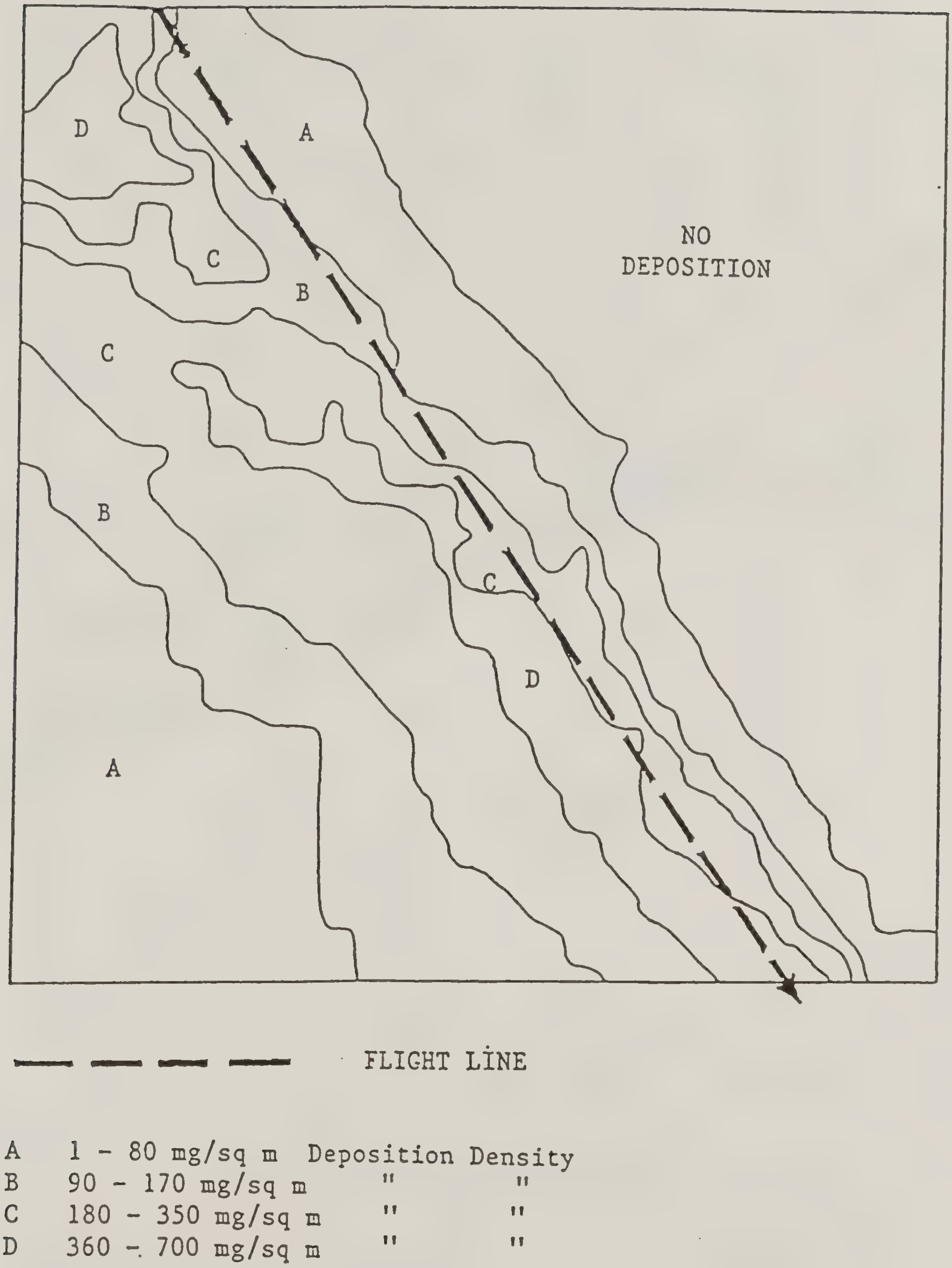
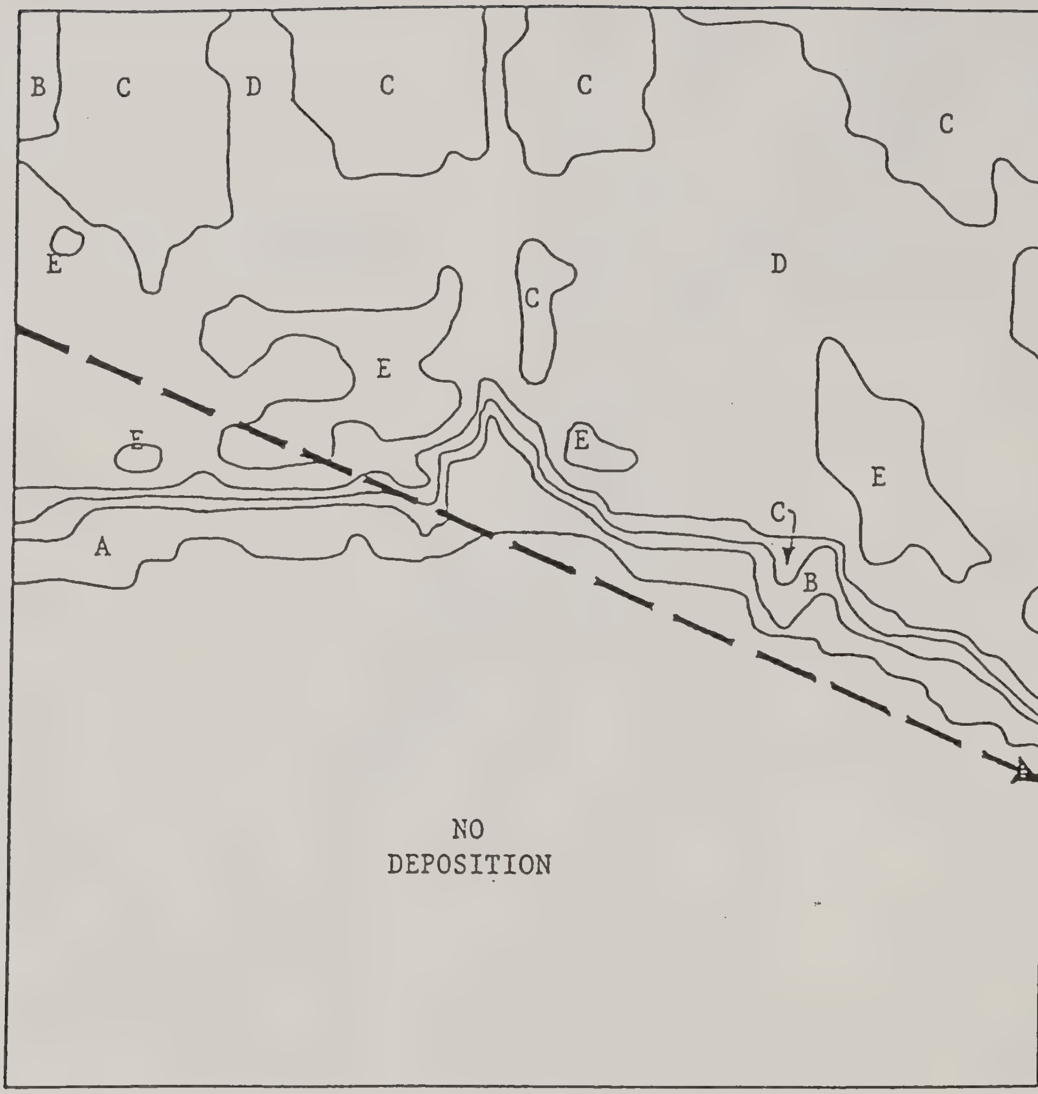


Figure 8: Trial FS2 deposition contour
(horizontal grid, U.S. Army Dugway Proving Ground)



FLIGHT LINE

A 1 - 10 mg/sq m Deposition Density
B 20 - 80 mg/sq m " "
C 90 - 170 mg/sq m " "
D 180 - 390 mg/sq m " "
E 400 - 800 mg/sq m " "

Figure 9: Trial FS3 deposition contour
(horizontal grid, U.S. Army Dugway Proving Ground)

— — — FLIGHT LINE

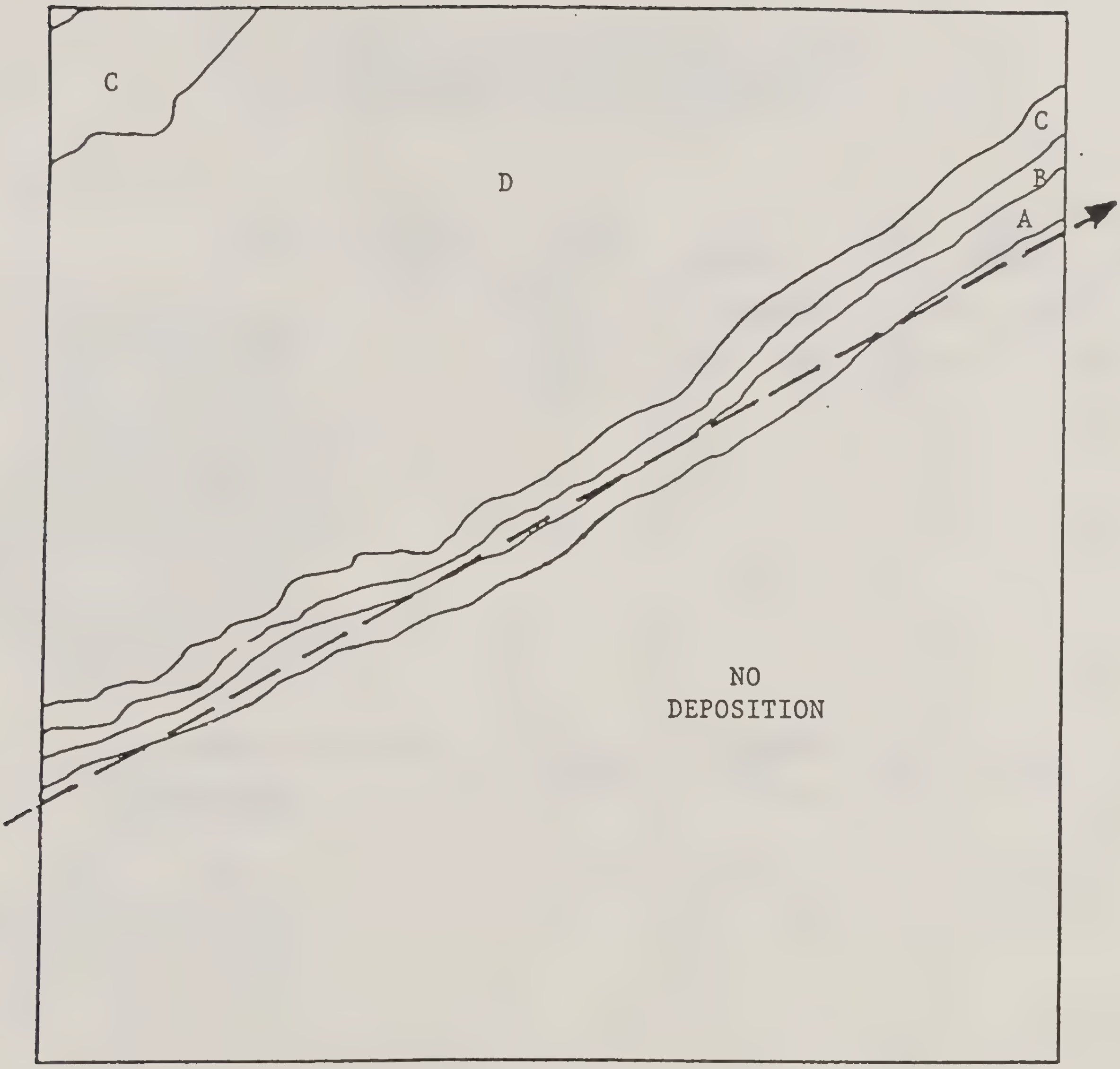
A 1 - 89 mg/sq m Deposition Density
B 90 - 170 mg/sq m " "
C 180 - 390 mg/sq m " "
D 400 - 800 mg/sq m " "

Figure 10: Trial FS4 deposition contour
(horizontal grid, U.S. Army Dugway Proving Ground)

— — — FLIGHT LINE

A 1 - 29 mg/sq m Deposition Density
B 30 - 80 mg/sq m " "
C 90 - 170 mg/sq m " "
D 180 - 390 mg/sq m " "

Figure 11: Trial FS5 deposition contour
(horizontal grid, U.S. Army Dugway Proving Ground)



FLIGHT LINE

A 1 - 29 mg/sq m Deposition Density
B 30 - 80 mg/sq m " "
C 90 - 170 mg/sq m " "
D 180 - 390 mg/sq m " "

Figure 12: Trial FS6 deposition contour
(horizontal grid, U.S. Army Dugway Proving Ground)

Table 1: Scope of the 1972 MISS Test

Test Phase	Spray System	Trial No.	Location	Date of Trial	Release Ht (m)	Purpose
A	FS	FS1 FS2 FS3	DPG	27 April 27 April 27 April	150 - 300	Establishment of a baseline with the FS system compatible with Zectran® spray license criteria. Deposition density, area coverage, droplet spectra, liquid recovery and swath width evaluated. Petri dishes containing spruce budworm larvae were placed at special sampling positions during Trial FS3 to evaluate Zectran® effectiveness.
B	MISS	FS4 FS5	DPG	24 June 24 June	150 - 300	Preliminary trials: deposition characteristics of the MISS system
C	MISS	FS6	DPG	25 June	150 - 300	Comparison with the baseline established in Test Phase A to demonstrate that the MISS system meets Zectran® license criteria
D	MISS	FS7	Lolo National Forest	29 June	145 - 150	Demonstration of the effectiveness of the MISS system to suppress spruce budworm larvae in an infested coniferous forest

Table 2: Summary of Meteorological Data and Spray System Variables for Trials FS1 through FS6

	FS1	FS2	FS3	FS4	FS5	FS6
Time of Day (MST)	07:17	09:15	18:22	09:06	10:43	06:08
Relative Humidity (percent)	28	28	29	ND	ND	83
1-m Air Temperature (deg C)	6.7	11.06	6.1	ND	ND	6.1
Temperature Difference (0.5 to 32 m) (deg C)	-2.5	-2.1	0.0	ND	ND	ND
2-m Wind Speed (m/sec)	1.5	2.0	2.2	(1.0)	2.0	(3.5)
48-m Wind Speed (m/sec)	1.5	2.2	2.0	ND	ND	3.5
2-m Wind Direction (deg)	240	345	60	(60)	35 *	(15)
Aircraft Heading (deg)	240	24	352	130 *	352 *	300 *
Air Speed (m/sec)	65.3	65.8	66.3	59.1	60.1	60.1
Aircraft Height (m)	53.0	61.9	100.0	45.7	45.7	42.7

ND No data available

( ) Estimated by Taylor et al. (1972)

* Estimated value

Table 3: Aircraft Characteristics for Trials FS1 through FS6

Aircraft Type	C-47
Weight (kg)	9702.0
Wing Span (m)	28.82
Planform Area (sq m)	93.79
Drag Coefficient	0.1
Propeller Radius (m)	1.77
Propeller Efficiency	0.8
Blade RPM	2550.0
Number of Nozzles Assumed	46
Nozzle Type Assumed	8020
VMD Assumed (μm)	211.1
Flow Rate (gal/min)	150.0
Spraying Speed (m/sec)	66.82

Table 4: Drop Size Distribution Assumed for Trials FS1 through FS6

Drop Diameter (micrometers)	Mass Fraction
45.88	0.0115
73.73	0.0274
106.35	0.0521
138.62	0.1180
171.03	0.1649
203.42	0.1674
235.88	0.1698
268.32	0.0843
301.32	0.0267
334.77	0.0435
366.72	0.0080
398.21	0.0145
430.71	0.0358
463.18	0.0422
495.68	0.0014
528.67	0.0325

	1.0000

3. FSCBG Simulation of Field Test Data

Meteorological conditions and aircraft and spray system variables for trials FS1 through FS6 were used to simulate field test deposition data with the Forest Service Cramer-Barry-Grim (FSCBG) aerial spray model. FSCBG predicts the transport and behavior of pesticide sprays released from aircraft. Technical aspects of the FSCBG model are discussed in Teske et al. (1993). The operation of the model is described in Teske and Curbishley (1991 and 1994).

FSCBG generates deposition data along a line perpendicular to the aircraft flight path. This line corresponds to the x-axis in Figures 13 through 18 (plots of the grid deposition data for trials FS1 through FS6, respectively).

Since the FS spray system used in the three trials of interest was not described in Taylor et al. (1972), the spray system type and corresponding drop size data for Zectran® were obtained by private communication with John W. Barry (USDA Forest Service). Drop size data is shown in Table 4. The spray system used to model the trials consists of 8020 fan nozzles oriented downward at 90 degrees to the free stream wind. Forty-six nozzles were positioned evenly under the wing over seventy-five percent of the wing span. The spray system flow rate was 150 gal/min for all six trials.

Taylor et al. (1972) state that the Zectran® formulation used in the trials was either oil-based or kerosene-based but do not specify which type of formulation was used in each trial. In the course of modeling the six trials it was apparent that FS3 and FS4 were conducted with the oil-based formulation and the remaining trials were conducted with the kerosene-based formulation. Spray system variables were adjusted accordingly.

The MISS spray system used was also not described in Taylor et al. (1972). For the purposes of this report, it was assumed that the drop size data for Zectran® was the same for the MISS system as for the FS system.

Figures 13 through 18 show the FSCBG predictions for ground deposition on Printflex cards, given as deposition density in mg/m^2, for trials FS1 through FS6. The predictions are shown compared to grid deposition data. Adjustments were made to the FSCBG predictions to reflect the uncertainty in spray system, formulation characteristics and accuracy of test conditions. No drop number data were available for correlation to FSCBG.

Considering these uncertainties and the scatter in the test data, FSCBG predictions compare well with the grid deposition data, especially in the case of trial FS2 (Figure 14), where the shape and level of predicted deposition is similar to observed deposition. In trial FS3 there is considerable scatter in the field test data, but the simulation still captures the shape and level of the deposition fairly well. FSCBG predicts the right level of deposition, but not the right shape, for trial FS6. In this trial the deposition profile shows a high level of deposition over the entire measured portion of the grid. For trials FS1, FS4 and FS5, FSCBG predicts the right shape of ground deposition, but a higher level than was observed.

The differences in level and shape of the predicted and observed depositions for some of the trials are probably due to a combination of incorrect spray system modeling, errors in characterization of the Zectran® formulation, and experimental error in

tabulated test conditions. Even accounting for all of these sources of discrepancy, the FSCBG predictions shown here are similar to many of the simulations made as part of the ongoing FSCBG validation study (MacNichol and Teske 1993a, 1993b, 1994a, 1994c).

Figures 19 through 24 compare field test deposition values (in mg/sq m) to simulated values of deposition at the same axial distance from the aircraft flight line. The least squares slopes through the data comparisons are given in Table 5, as are the correlation coefficients, R^2, for each trial. These values are very promising in light of the discrepancies just cited. Average correlation to mass for all of the trials is $R^2 = 0.61$. Omitting trial FS3, which shows a large amount of scatter in the field test data, the average correlation to mass for the five remaining trials is $R^2 = 0.70$.

As indicated by Table 5, trials FS1 and FS2 show the best comparison between simulated and field test deposition for the FS system, and trial FS6 shows the best comparison for the MISS system. Each of these systems appears to have been adequately modeled for the purposes of this analysis; correlation of predicted and observed deposition for the remaining trials would probably improve with better modeling of the spray system and more accurate drop size data.

Throughout the ongoing validation effort previously mentioned, FSCBG predictions of mass deposition have been consistent with measured field test data. The average correlations to mass for other field tests studied are: $R^2 = 0.62$ for the 1991 Davis Virus Spray Trials (MacNichol and Teske 1994a), $R^2 = 0.86$ for the 1974 Rennic Creek Trials (MacNichol and Teske 1994b), and $R^2 = 0.30$ for the C-130 Spray Trials (MacNichol and Teske 1993a). Drop size distribution data were estimated for all of these tests. This is true for the 1972 MISS test as well. Nevertheless, the average correlation to mass for the trials examined here, $R^2 = 0.61$, is an acceptable value for operational field tests (MacNichol and Teske 1994a).

Although no mass data were available for the 1988 Davis Spray Characterization Trials, a swath width was predicted for each trial. Correlation of FSCBG predicted swath width to the field test swath width was $R^2 = 0.66$ (MacNichol and Teske 1993b). The current report also shows predicted swath width to be somewhat smaller than observed swath width, as seen in the next section.

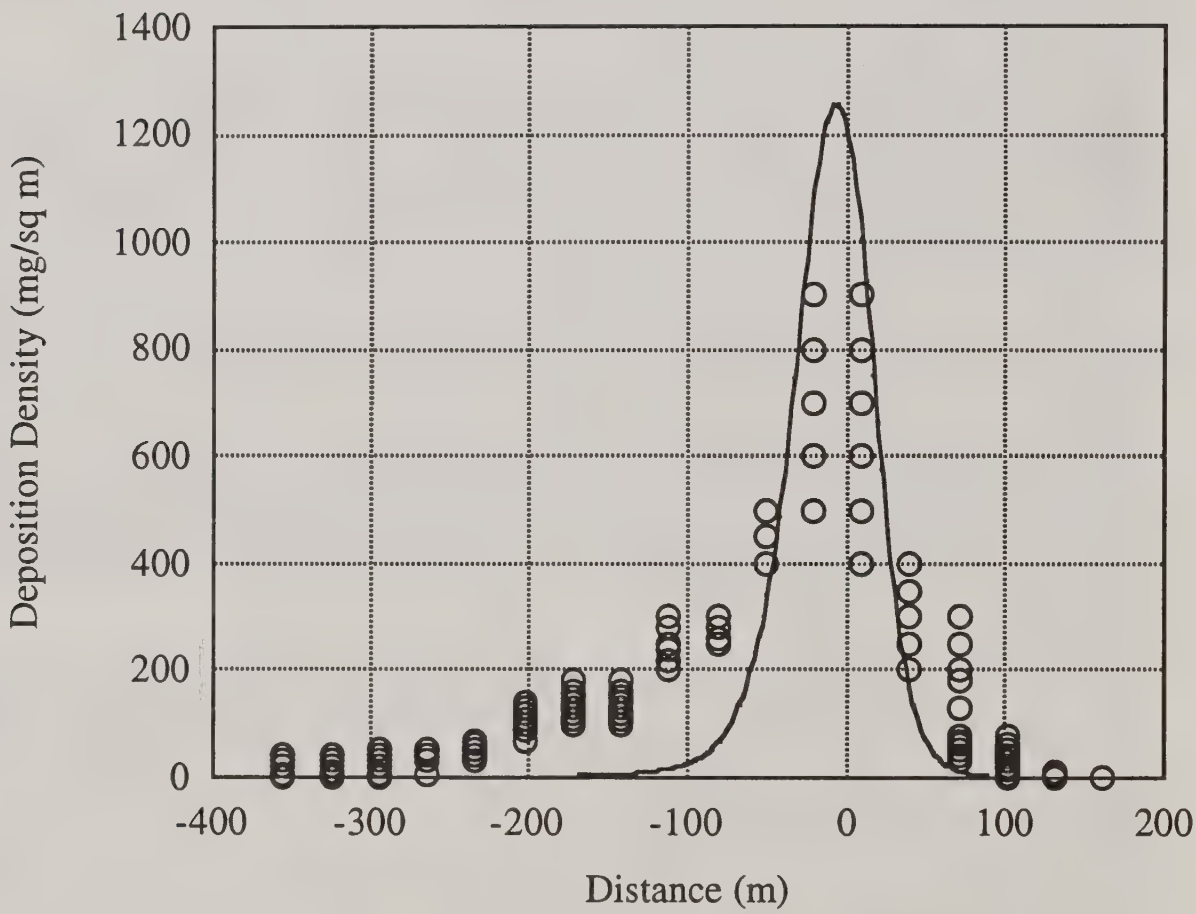


Figure 13: Trial FS1: observed and simulated ground deposition at release height = 53.0 m. Observed data are shown as open circles and simulated data are shown as a solid line.

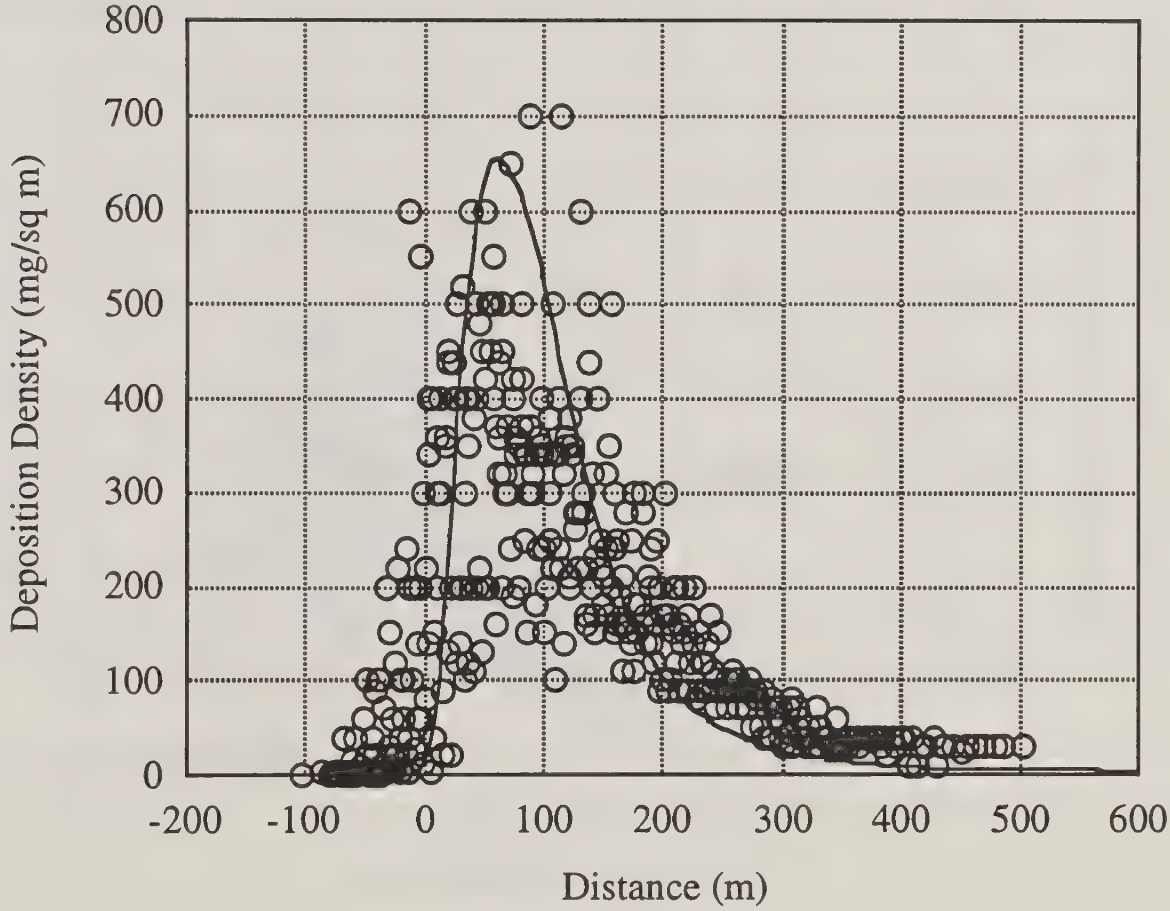


Figure 14: Trial FS2: observed and simulated ground deposition at release height = 61.9 m. Observed data are shown as open circles and simulated data are shown as a solid line.

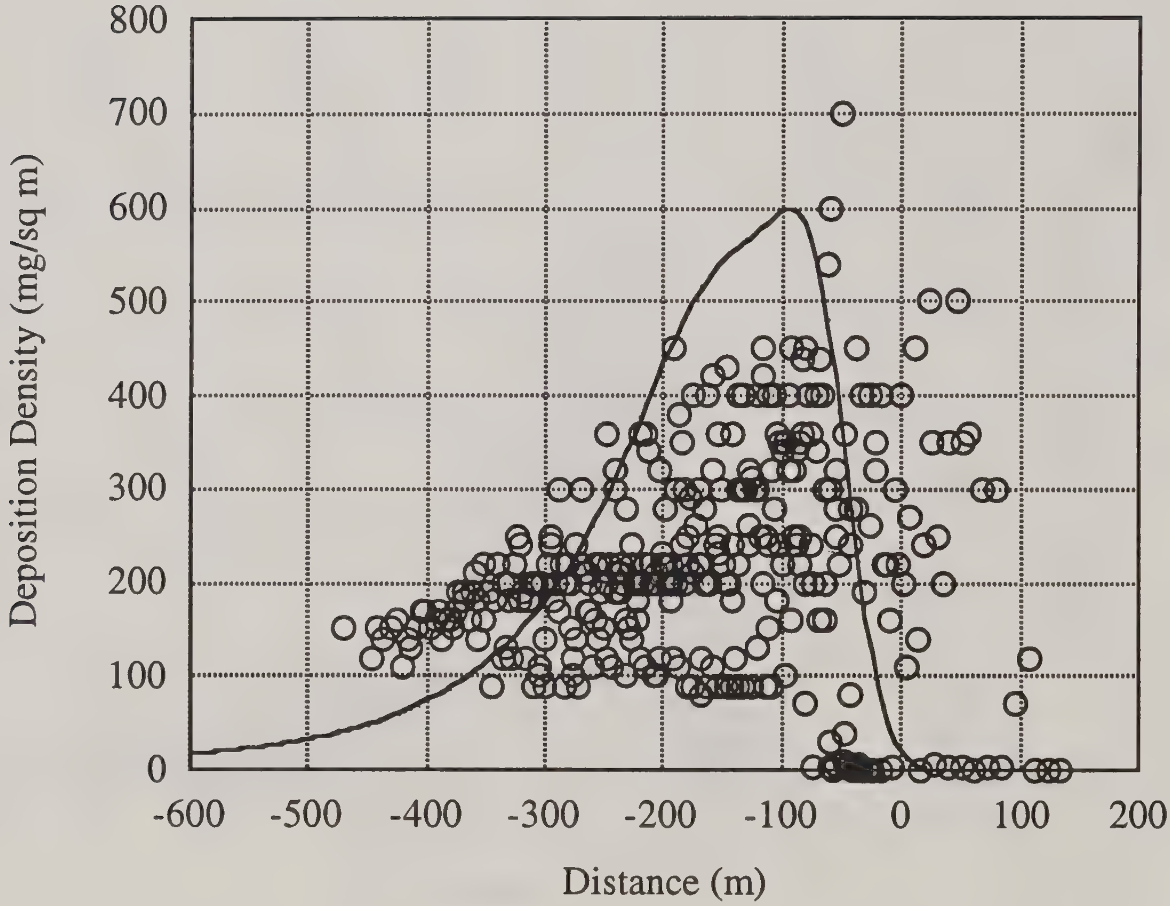


Figure 15: Trial FS3: observed and simulated ground deposition at release height = 100.0 m. Observed data are shown as open circles and simulated data are shown as a solid line.

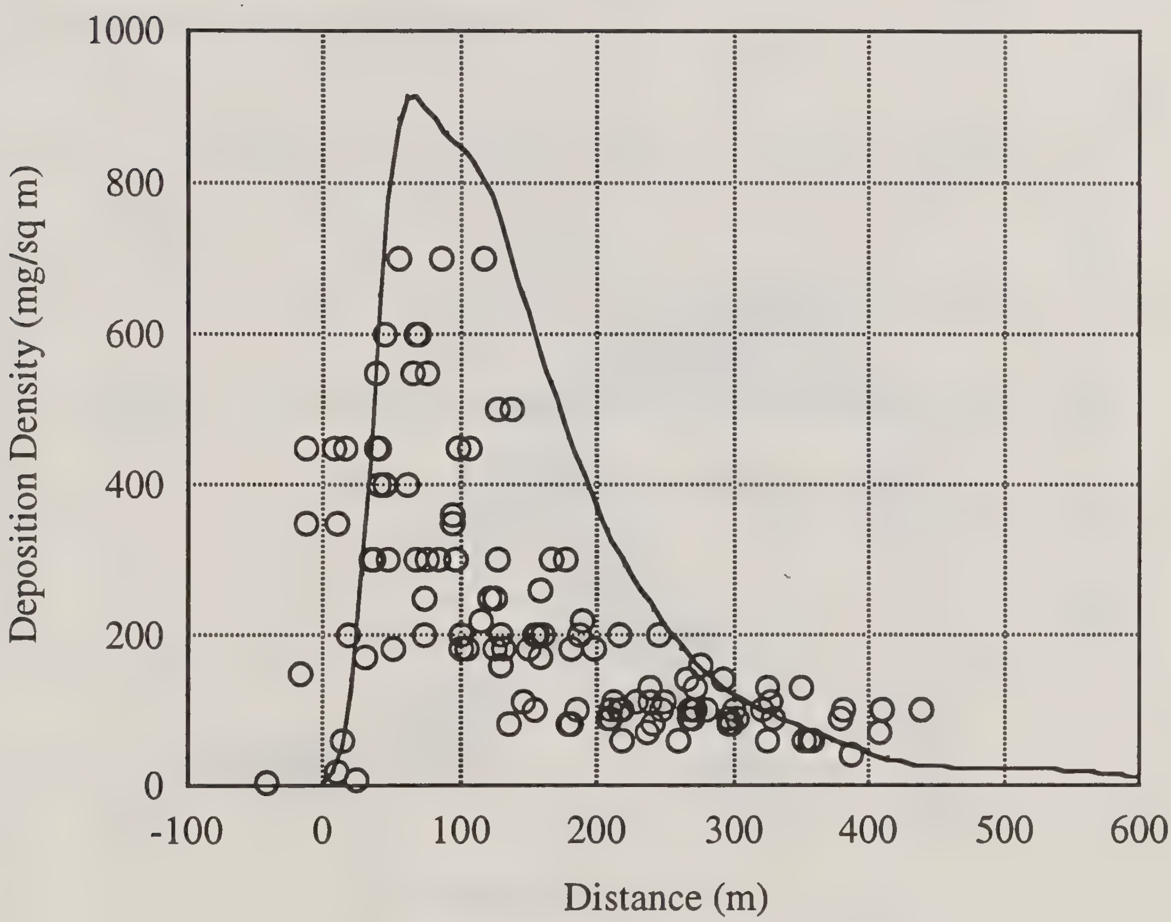


Figure 16: Trial FS4: observed and simulated ground deposition at release height = 45.7 m. Observed data are shown as open circles and simulated data are shown as a solid line.

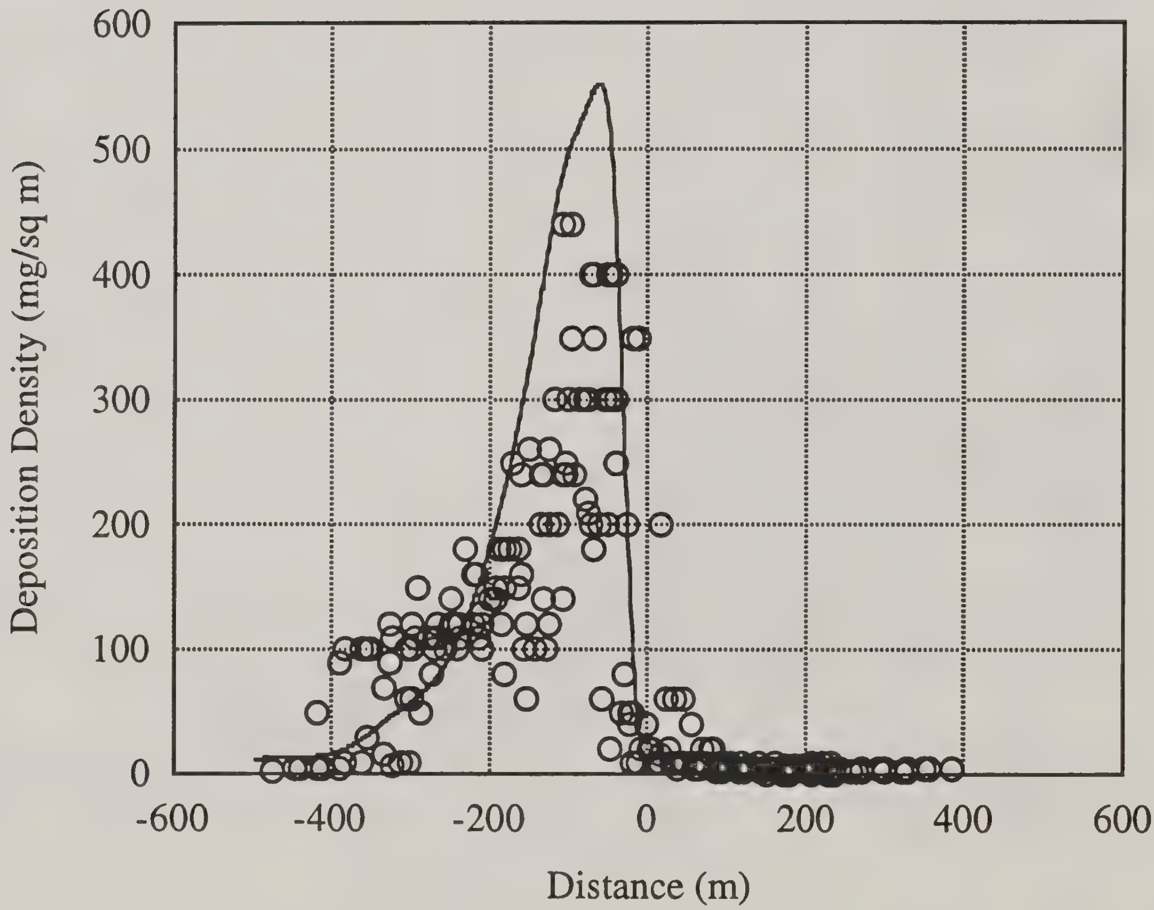


Figure 17: Trial FS5: observed and simulated ground deposition at release height = 45.7 m. Observed data are shown as open circles and simulated data are shown as a solid line.

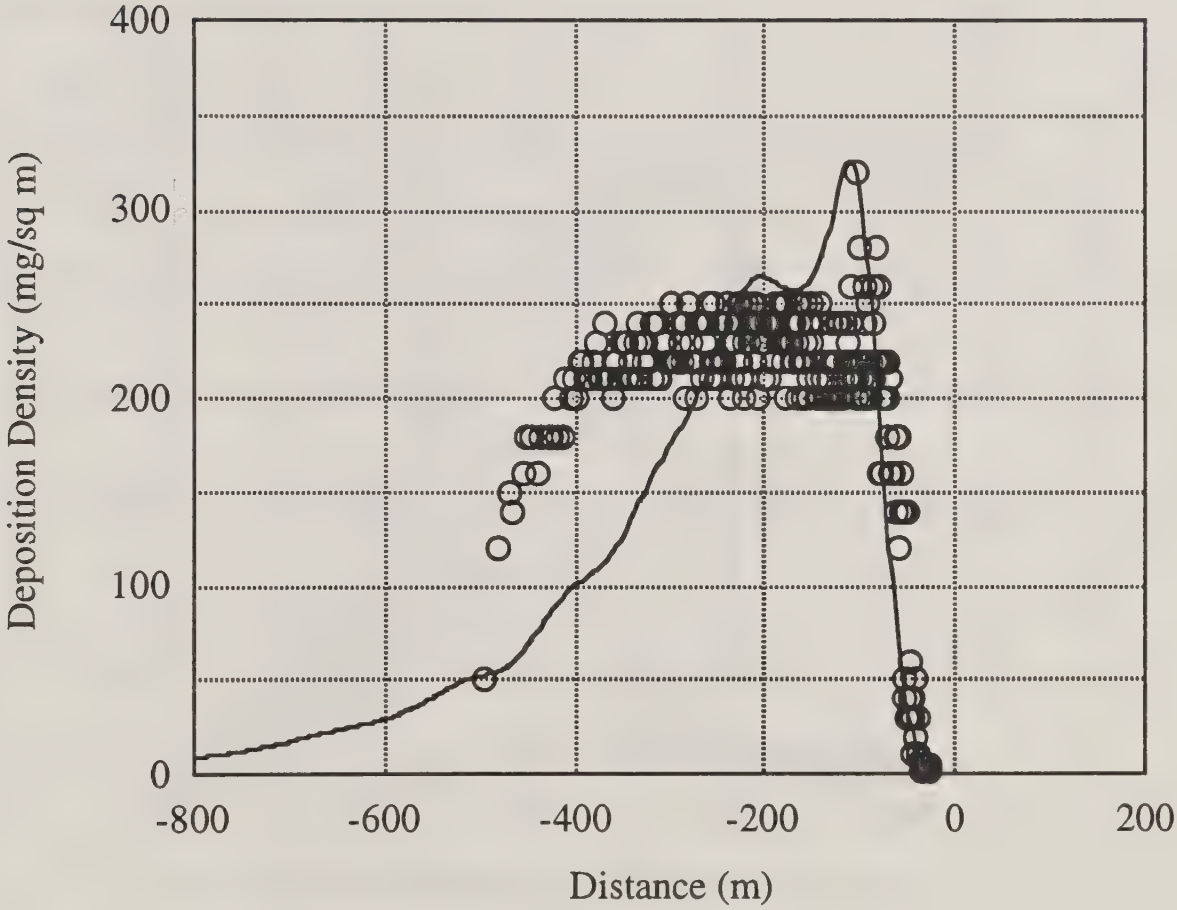


Figure 18: Trial FS6: observed and simulated ground deposition at release height = 42.7 m. Observed data are shown as open circles and simulated data are shown as a solid line.

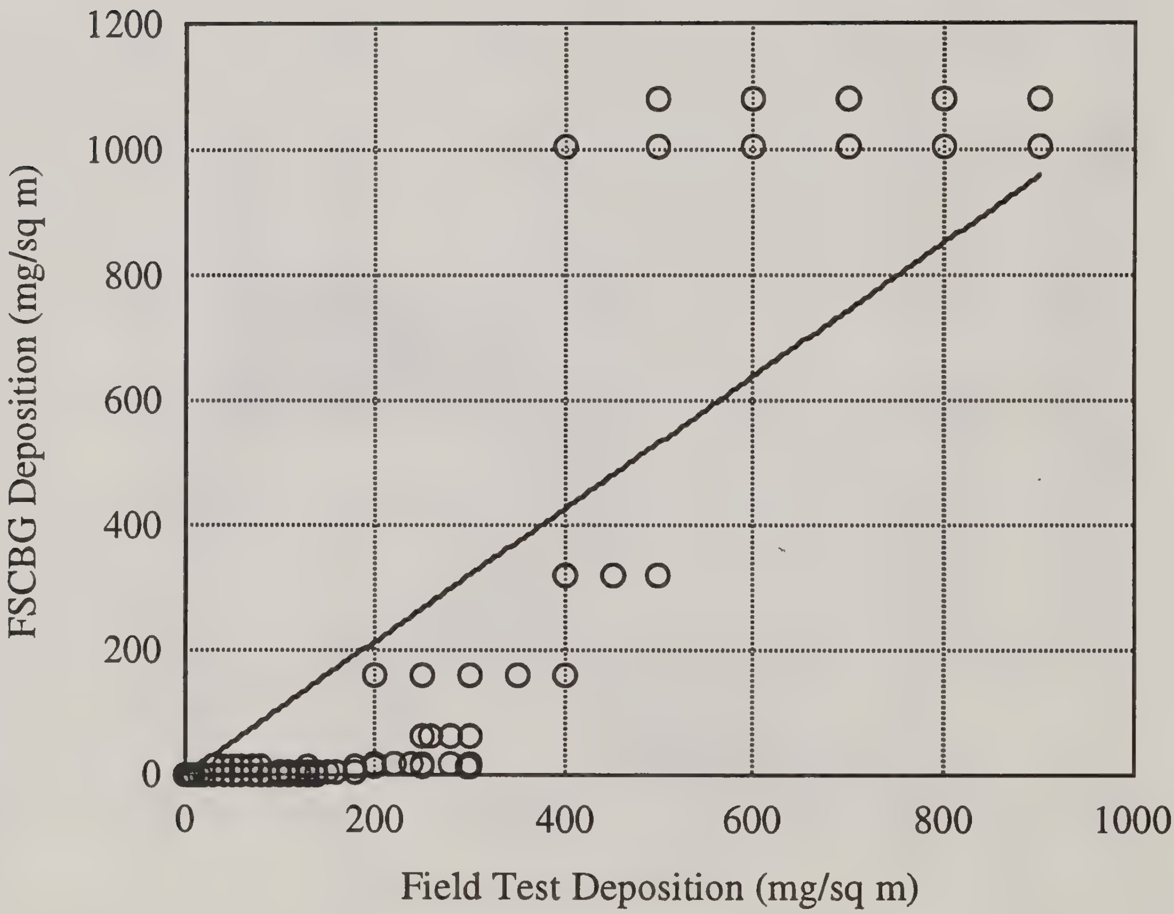


Figure 19: Simulated versus field test deposition for trial FS1:
least squares slope =1.06, R^2= 0.75

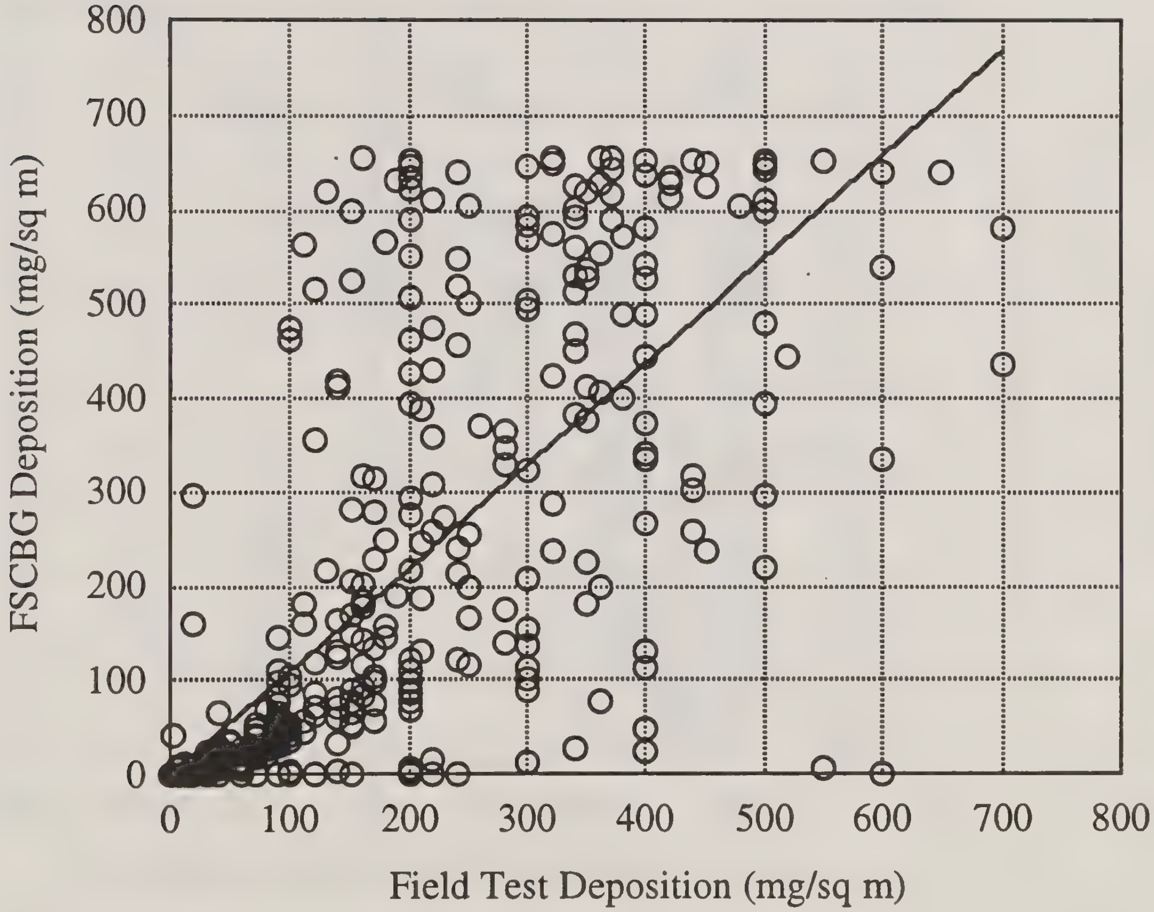


Figure 20: Simulated versus field test deposition for trial FS2: least squares slope =1.10, R^2= 0.72

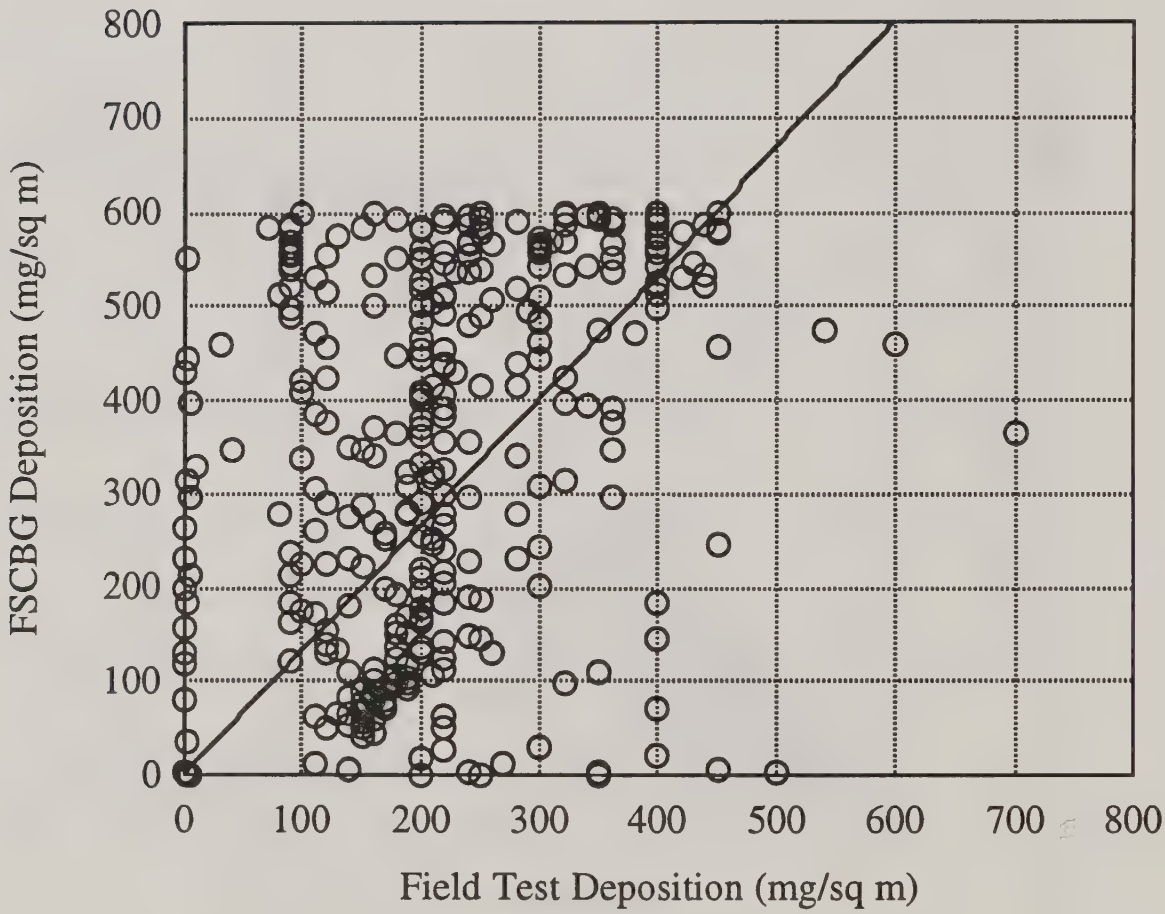


Figure 21: Simulated versus field test deposition for trial FS3:
Least squares slope =1.34, R^2= 0.17

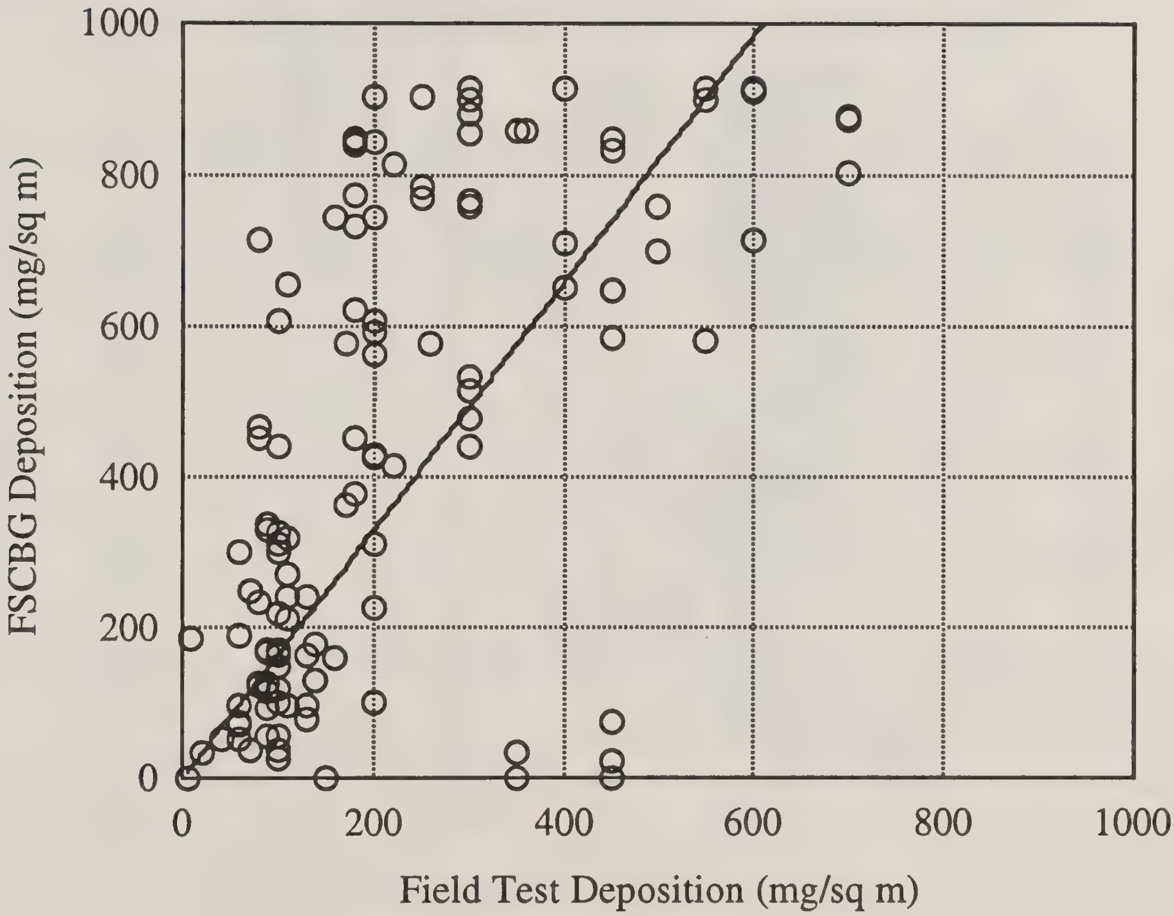


Figure 22: Simulated versus field test deposition for trial FS4:
least squares slope =1.64, R^2= 0.59

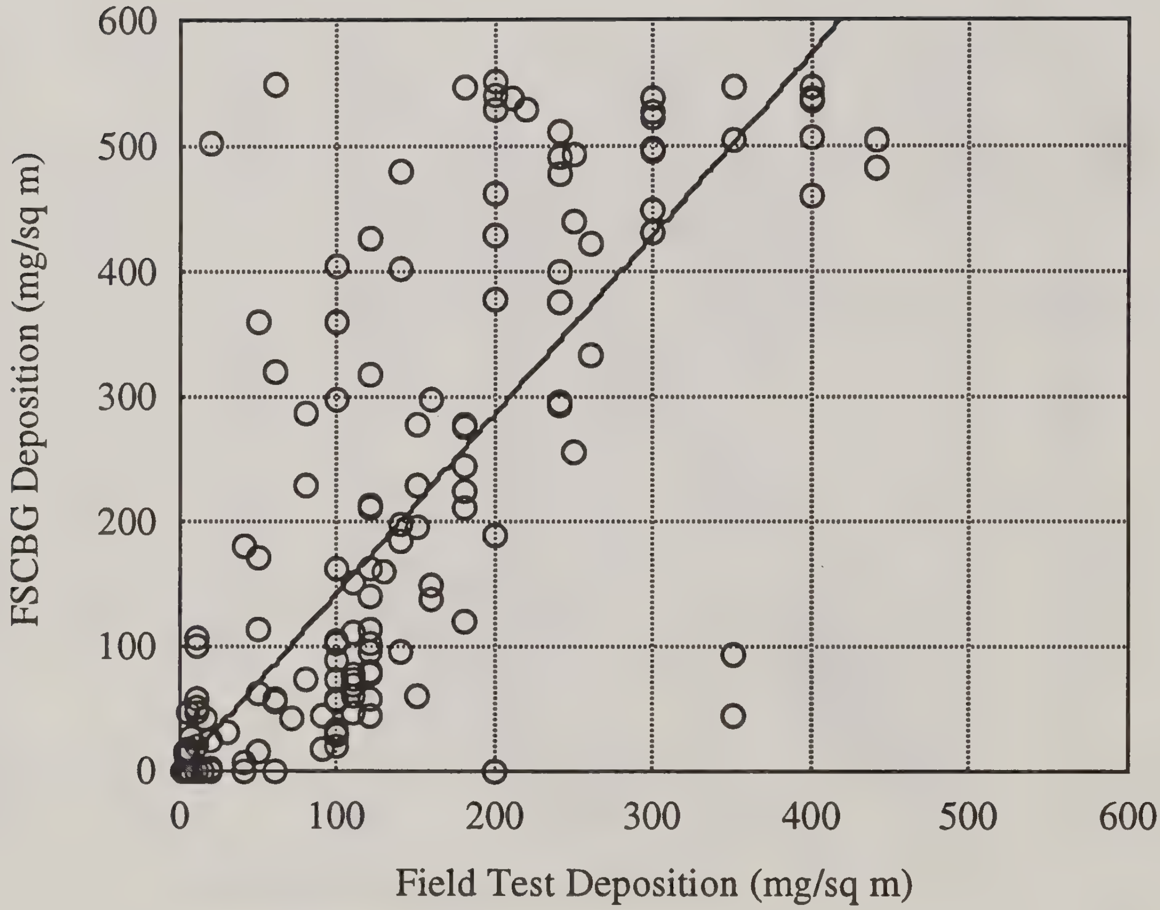


Figure 23: Simulated versus field test deposition for trial FS5:
least squares slope =1.43, $R^2 = 0.74$

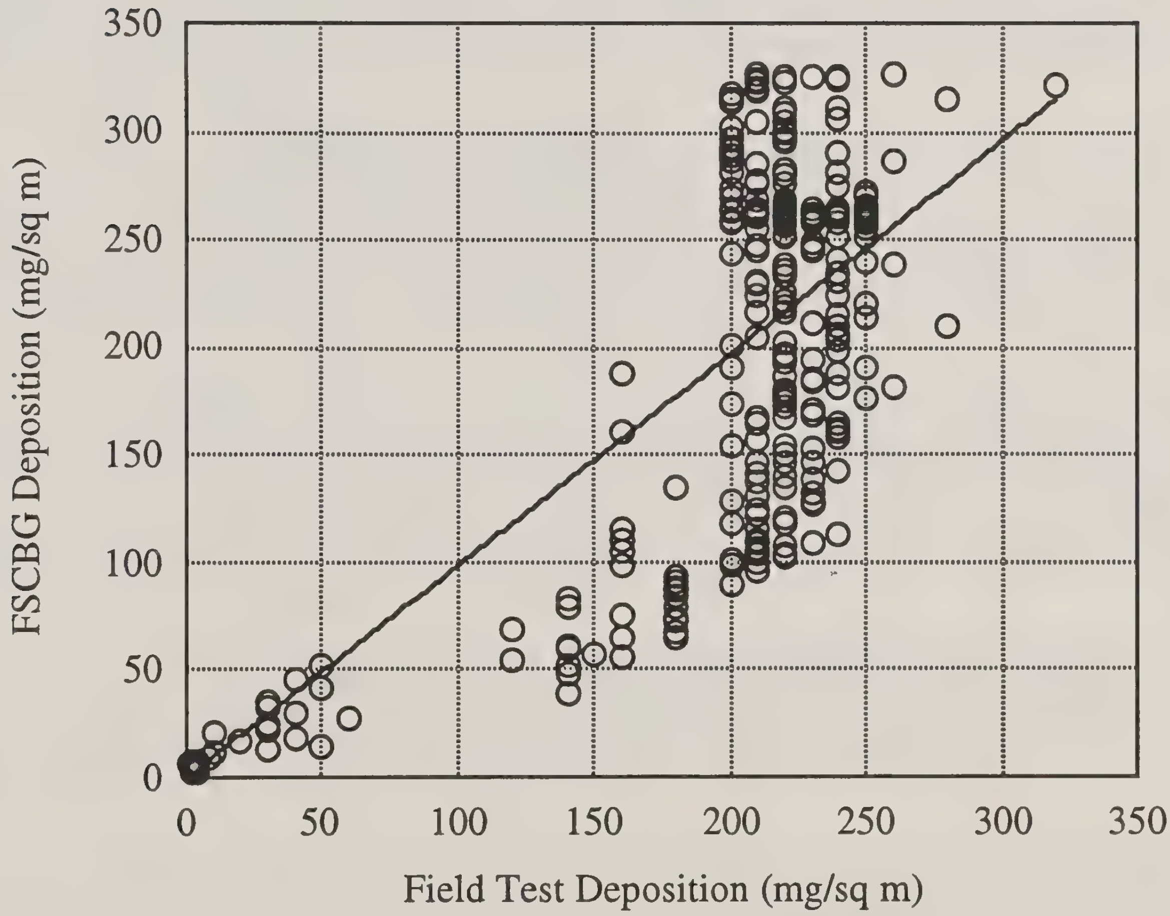


Figure 24: Simulated versus field test deposition for trial FS6: least squares slope =1.00, R^2= 0.71

Table 5: Least Squares Slope and Correlation Coefficient for Trials FS1 through FS6

Trial #	Least squares slope	Correlation to mass (R^2)
FS1	1.06	0.75
FS2	1.10	0.72
FS3	1.34	0.17
FS4	1.64	0.59
FS5	1.43	0.74
FS6	1.00	0.71
Average (all trials)		0.61
Average (FS1-FS2, FS4-FS6)		0.70

4. FSCBG Simulation of Biological Response

The purpose of these spray trials was to evaluate how effective the MISS might be in suppressing the western spruce budworm by defining a footprint (swath pattern) for the C-47. To this end, an effective swath width was determined for each of the six trials. The lowest deposition density associated with areas of 100% insect mortality rate in open terrain was determined to be 90 mg/m^2 of the Zectran® mixture (Taylor et al. 1972). Effective swath width was determined by the deposition pattern over the grid: wherever there was deposition greater than 90 mg/m^2 there would be 100% insect mortality within 24 hours of application.

Table 6 shows the effective swath width as calculated by Taylor et al. (1972) compared to the effective swath width predicted by FSCBG. Trials FS2 through FS5 compare well: the effective swath widths predicted for FS2, FS3 and FS4 are within 10 % of the observed values, and the prediction for FS5 is within 15% of the observed value. The discrepancies in predicted and observed effective swath widths for trials FS1 and FS6 result from poor prediction of the shape of deposition for both of these trials.

As previously mentioned, the MISS trials provide a unique opportunity to evaluate dose/response: live insects (spruce budworm larvae, SBWL) were placed on the test grid in petri dishes and their status was evaluated at 6, 24 and 48 hours after the spray run. Although Taylor et al. (1972) state in their test description that the SBWL were present on the grid for trial FS3, they present a table of insect mortality data for trials FS2, FS4 and FS6 only. Thus, field test data from these three trials are compared to FSCBG simulation of Zectran® dosages deposited over the grid.

Taylor et al. (1972) calculate insect mortality rate by determining the percentage of dead SBWL counted at 6, 24 and 48 hours after application of the Zectran® mixture over the grid. No data are given for specific locations on the grid; only a total count of live and dead SBWL is shown. Mortality rate data for all three trials (FS2, FS4 and FS6) are only available at 24 hours after application.

Table 6 compares the mortality rate data from Taylor et al. (1972) to the predicted mortality rate based on FSCBG effective swath width. The predicted and actual mortality rates compare well, even for the trials where effective swath width was not closely predicted. It should be noted that the levels given only indicate the level of 100% mortality; the contour plots of ground deposition for trials FS1 through FS6 (Figures 7 through 12) show that deposition is not uniform, and there may be pockets of less than 100% mortality over parts of the grid.

Figures 25, 26 and 27 show the specific levels of insect mortality rate over the grid and the predicted effective swath for trials FS2, FS4 and FS6. Trial FS4 shows the closest correlation of predicted to observed effective swath (Table 6). However, Figure 26 shows that although the predicted swath encompasses most of the areas of 100% insect mortality, several pockets of lower deposition, indicating less than 100% mortality, can be seen within the swath. The contour plot of ground deposition for trial FS4 (Figure 10) shows two large areas of low deposition on the edges of the grid (the areas denoted by letter A); these areas are within the effective swath width shown in Figure 26. Similar pockets of lower deposition (and thus lower insect mortality) can be seen in Figure 25. It

is apparent that the edges of the effective swaths for these two trials are not straight; deposition edge effects have an impact on the area of effective application.

Figure 27, which shows predicted and observed data for trial FS6, does not show pockets of lower deposition within the effective swath. For this trial, FSCBG under-predicts the spread of deposition over the grid (Figure 18). More importantly, deposition continued beyond the edges of the grid (as evidenced by the high levels of deposition along all of the grid edge where deposition was measured). Therefore, the actual effective swath could have been wider than what was observed. There is no way to evaluate the edge of the swath in trial FS6. However, since the deposition contour plot for this trial (Figure 12) shows much smoother edges of deposition than the contour plots for trials FS2 and FS4, it can be assumed that there would be few pockets of lower deposition within the effective swath if the entire deposition pattern had been captured.

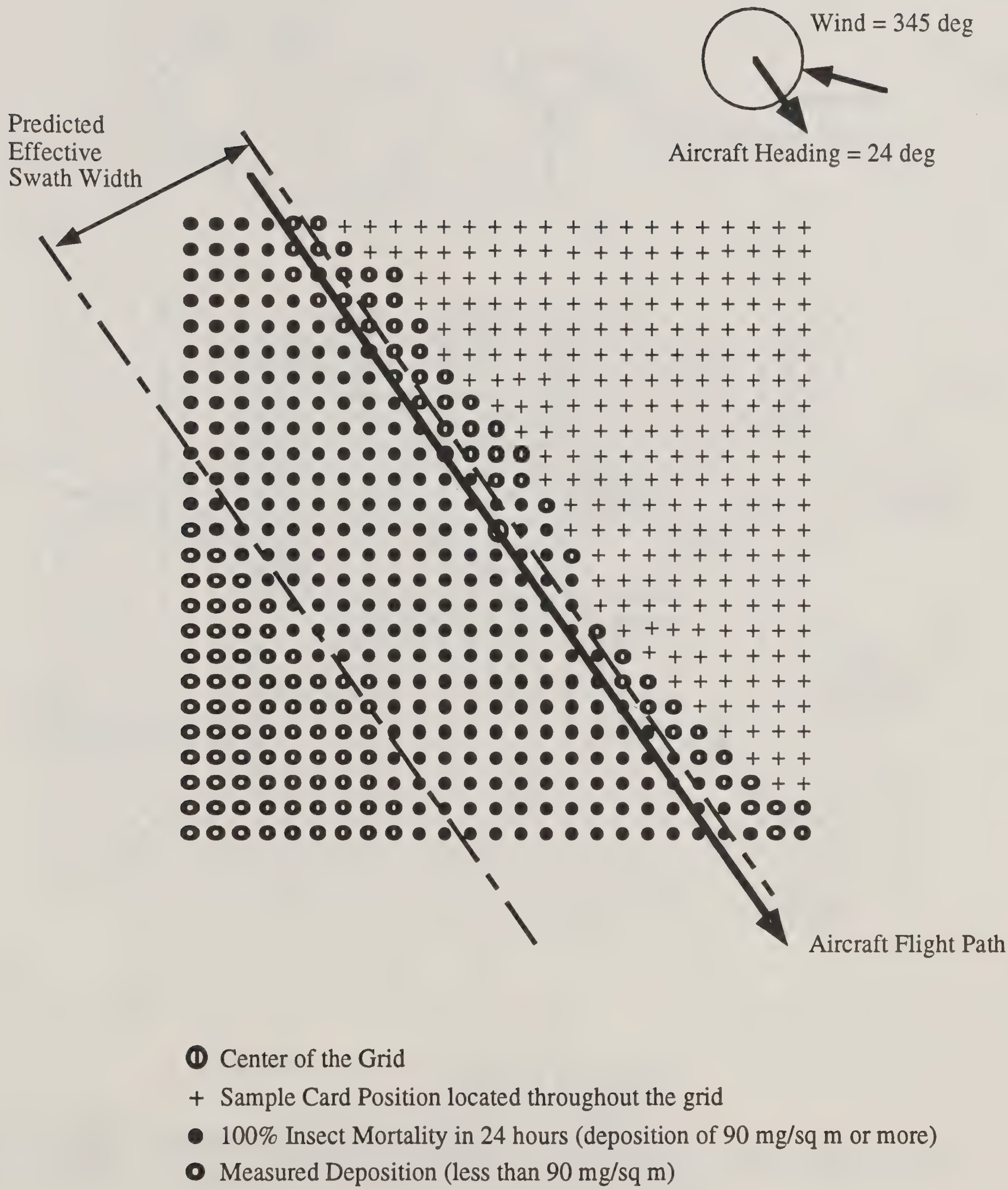


Figure 25: Insect mortality data and predicted effective swath width for trial FS2, shown on the horizontal grid at DPG

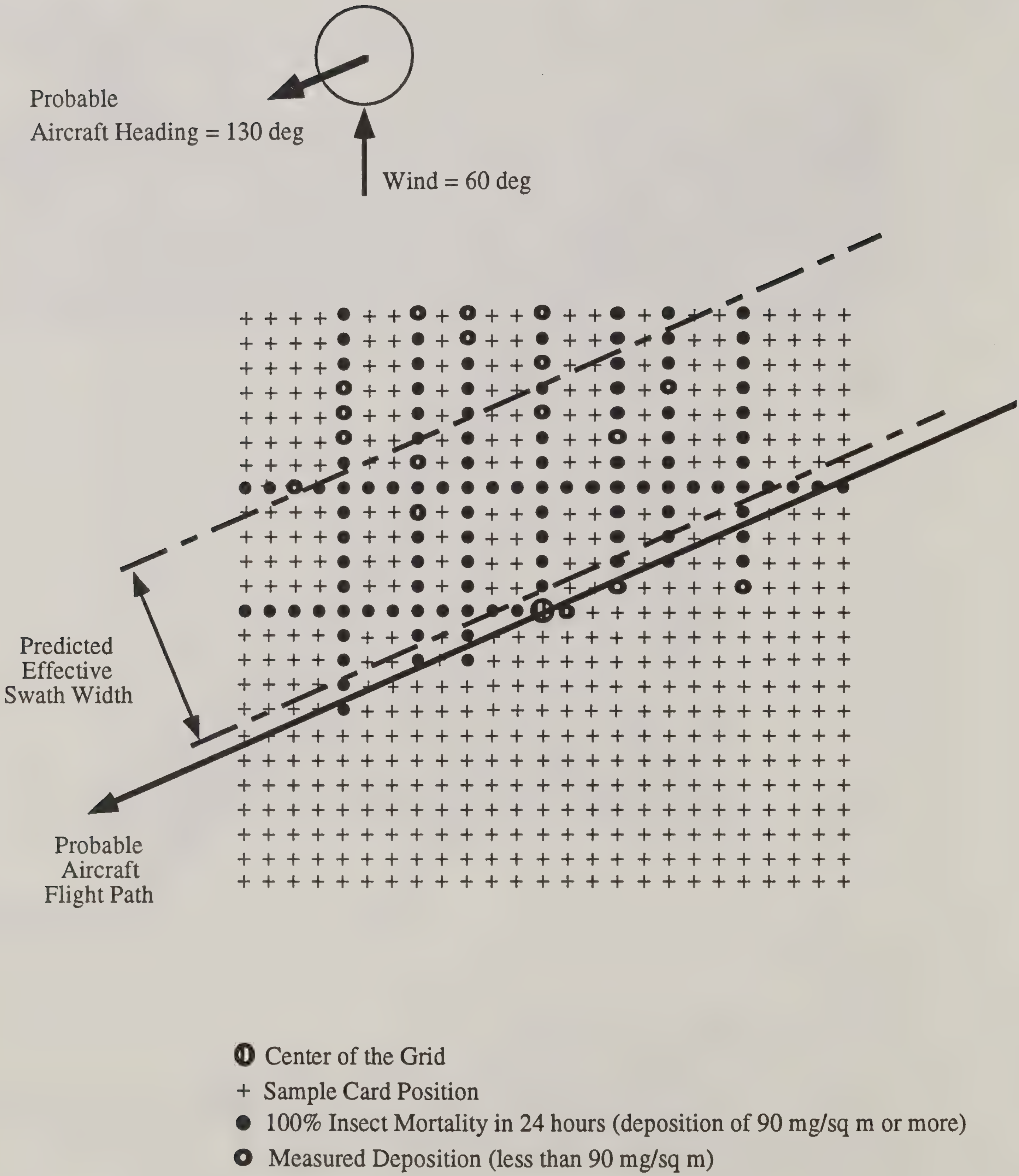


Figure 26: Insect mortality data and predicted effective swath width for trial FS4, shown on the horizontal grid at DPG

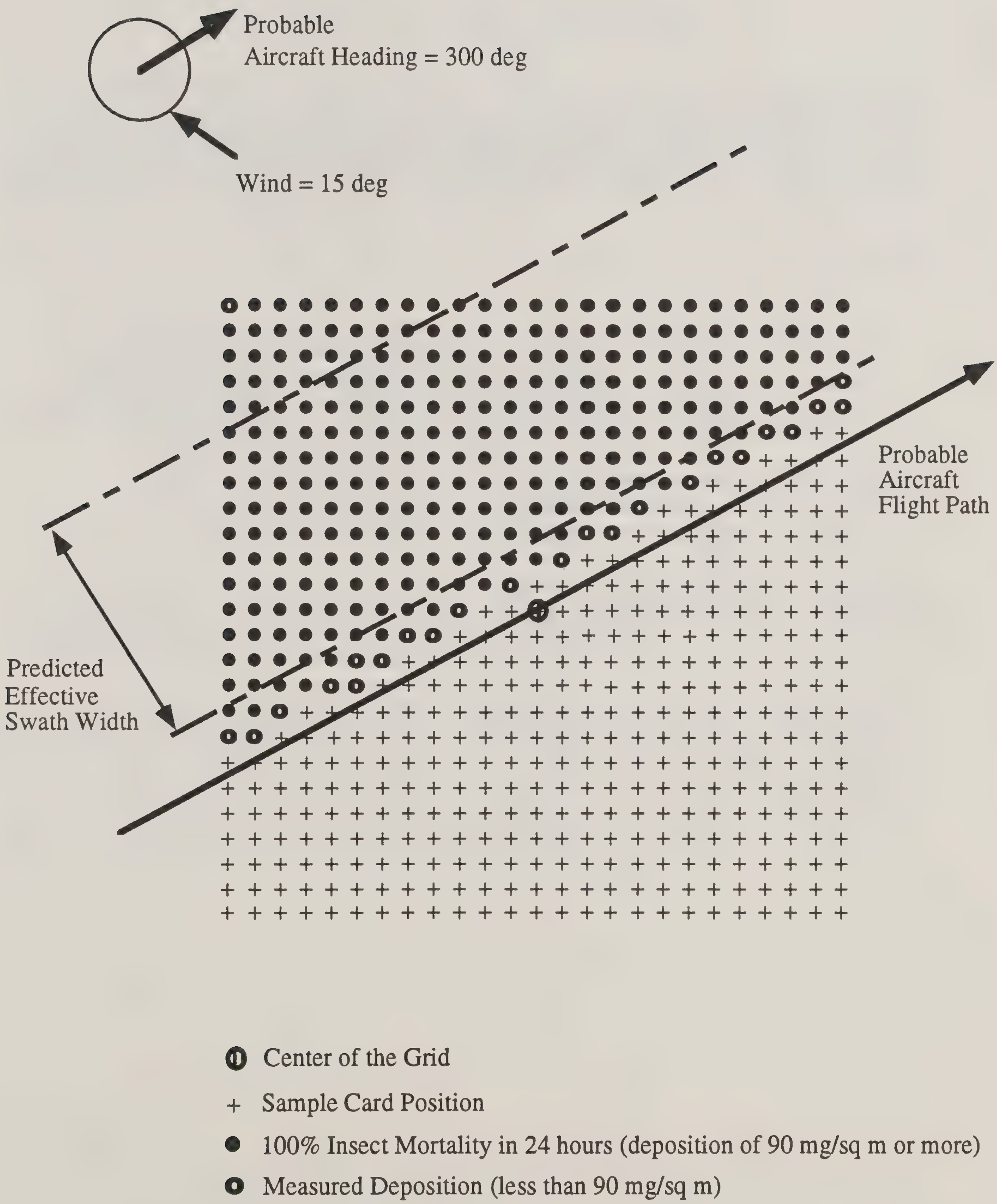


Figure 27: Insect mortality data and predicted effective swath width for trial FS6, shown on the horizontal grid at DPG

Table 6: Effective Swath Width and Insect Mortality Rate for Trials FS1 through FS6.

Trial #	Release height m	Effective swath width (Field Test) m	Effective swath width (Predicted) m	Mortality Rate (Observed)	Mortality Rate (Predicted)
FS1	53.0	274	120		
FS2	61.9	274	200	51 %	47 %
FS3	100.0	365	360		
FS4	45.7	335	310	47 %	52 %
FS5	45.7	304	260		
FS6	42.7	426	360	40 %	43 %

5. Conclusions and Recommendations

FSCBG predictions of the 1972 C-47 MISS trials ground deposition data show good correlation, with an overall $R^2 = 0.61$ for mass. This value is within acceptable levels for operational field tests. While extensive dose/response prediction was not possible because of the lack of detailed field test data, expected levels of insect mortality rate agreed very well with observed mortality rates.

The trials would have been more accurately modeled with the following data available:

1. exact spray system description (for both spray systems used), particularly the type and placement of nozzles.
2. exact drop size distribution (nozzle atomization).
3. more detailed meteorological data over the entire test grid.
4. more detailed measurement of the aircraft variables, particularly release height and flight path over the test grid.
5. consistent methods for deposition sampling throughout the test (as previously mentioned, some of the trials were evaluated visually and some using ASCAS, and ASCAS estimates were adjusted to give "realistic" results).

Similar recommendations have been made following modeling of other spray trials conducted in the past, in particular MacNichol and Teske (1994c). Accurate drop size characteristics, detailed meteorological measurements, and timely interpretation of deposition cards are essential to accurately model field tests.

It is apparent from looking at the biological response data that deposition pattern edge effects are an important factor in the determination of effectiveness of application. FSCBG simulations of the three trials for which biological data are available show good correlation with observed insect mortality rate. However, for those trials in which the deposition contour plots show significant pattern edge effects, the insect mortality rate in specific areas of the grid is not being properly predicted. Further study of pattern edge effects is undertaken in the next report on the 1972 MISS test, Part 3.

6. Acknowledgment

The authors would like to acknowledge the support of John W. Barry, Project Officer, USDA Forest Service, Forest Pest Management (Davis, CA). The 1972 MISS trials were made possible through the cooperative effort of U.S. Army Deseret Test Center personnel and USDA Forest Service personnel at Missoula Equipment Development Center (Missoula, MT), Region I Forest Insect and Disease Branch (Missoula, MT) and the Pacific Southwest Forest and Range Experiment Station (Berkeley, CA).

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United States
Department of
Agriculture

Forest Service

Forest Health
Protection

Davis, CA

C-47 Aircraft Spray Deposition

Part 3:

FSCBG Model Prediction of Deposition Edge Effects

FPM 95-16
June 1995

Pesticides used improperly can be injurious to human beings, animals, and plants. Follow the directions and heed all precautions on labels. Store pesticides in original containers under lock and key—out of the reach of children and animals—and away from food and feed.

Apply pesticides so that they do not endanger humans, livestock, crops, beneficial insects, fish, and wildlife. Do not apply pesticides where there is danger of drift when honey bees or other pollinating insects are visiting plants, or in ways that may contaminate water or leave illegal residues.

Avoid prolonged inhalation of pesticide sprays or dusts; wear protective clothing and equipment, if specified on the label.

If your hands become contaminated with a pesticide, do not eat or drink until you have washed. In case a pesticide is swallowed or gets in the eyes, follow the first aid treatment given on the label, and get prompt medical attention. If a pesticide is spilled on your skin or clothing, remove clothing immediately and wash skin thoroughly.

NOTE: Some States have restrictions on the use of certain pesticides. Check your State and local regulations. Also, because registrations of pesticides are under constant review by the U.S Environmental Protection Agency, consult your local forest pathologist, county agriculture agent, or State extension specialist to be sure the intended use is still registered.

FPM 95-16
C. D. I. Technical Note No. 95-05
June 1995

C-47 AIRCRAFT SPRAY DEPOSITION

PART 3:

FSCBG MODEL PREDICTION OF DEPOSITION EDGE EFFECTS

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Summary

This is the final part of a three-part study of the 1972 MISS test, an aerial spray field test conducted by the USDA Forest Service in cooperation with the U.S. Army Deseret Test Center. A C-47 USDA Forest Service aircraft applied the chemical insecticide Zectran® over receptors of Printflex detector cards and petri dishes containing target insect larvae. Six trials were conducted over the horizontal grid at the U.S. Army Dugway Proving Ground, Utah. In Part 1 of this report, a statistical analysis was performed on ground deposition data from the first three trials. In Part 2, FSCBG simulations of ground deposition were presented for the six trials, and dose/response was predicted where applicable. Although correlation between the FSCBG predicted deposition and the field test data was good, the deposition contours observed over the test grid showed irregular edges. In the present report, a sensitivity study is performed to evaluate the effect of changes in local meteorological conditions on the predicted position of ground deposition contour edges.

Table of Contents

List of Figures

List of Tables

1. Introduction

This is the final part of a three-part study of the Modular Internal Spray System (MISS) test conducted in the spring of 1972. The test was a cooperative effort by the USDA Forest Service (FS) and U.S. Army Deseret Test Center; it is described in detail by Taylor et al. (1972), and has been summarized in Parts 1 and 2 of this report (MacNichol, 1994 and MacNichol and Teske, 1995). Henceforth, Part 1 refers to: C-47 Aircraft Spray Deposition, Part 1, A Statistical Interpretation (MacNichol 1994). Part 2 refers to: C-47 Aircraft Spray Deposition, Part 2, FSCBG Model Prediction of Deposition and Biological Response (MacNichol and Teske, 1995).

The MISS was an airborne, modular, reusable, high capacity spray system developed by the U.S. Air Force (USAF) to meet Special Operations requirements. For this test, it was installed on a C-47 aircraft and tested with a formulation of the insecticide Zectran®. A FS spray system installed on a C-47 was included in the test as a baseline system. Six trials were conducted at the U.S. Army Dugway Proving Ground (DPG) in Utah, three to evaluate the FS spray system and three to evaluate the MISS spray system. These trials were conducted over open and flat desert terrain. The aircraft flew over a 0.8 km x 0.8 km horizontal grid with up to 625 sampling positions throughout the grid. A seventh trial was later conducted at Lolo National Forest in Montana for an operational demonstration of the MISS over forested terrain.

Ground deposition data from the MISS trials is presented in Taylor et al. (1972). For four of the six trials at DPG there were at least 600 sampling positions on the grid, and for these trials the abundance of deposition data gives a detailed representation of the "footprint" of the spray pattern. Thus, it is possible to examine the overall contour of deposition over the grid as well as the levels of deposition observed along discrete lines normal to the aircraft flight path.

In addition to a densely sampled grid array, three of the DPG trials also had special sampling stations with live western spruce budworm insect larvae. The MISS test is the only known test in which live insects were placed on the grid with deposition samples in order to look at the dose/response.

This report concludes the detailed analysis of the 1972 MISS test which has been presented in Part 1 and Part 2. For those reports, the field test ground deposition data from the DPG trials were organized into multiple lines of deposition perpendicular to the aircraft flight line. Field test data could then be compared to predicted deposition profiles generated with the Forest Service Cramer-Barry-Grim FSCBG model 4.3 (Teske et al. 1993). Part 1 presented a statistical analysis of the field test spray patterns in the first three trials. Multiple card line deposition data were used to establish a confidence interval for the spray patterns; FSCBG simulations of these spray patterns were compared accordingly.

In Part 2, deposition data for all six trials were modeled using FSCBG, and predicted deposition patterns and biological response were compared with actual field test data. Although the FSCBG predictions of deposition and insect mortality rate presented

in Part 2 compared well with field test data, the simulated deposition profiles for each trial represent an average of all card lines on the grid. When viewed as a contour plot over the grid, field test deposition data show variance as the aircraft crosses the grid: the edges of deposition at a given level are not straight. These edge effects are present to some degree in all of the MISS trials, and are the subject of this report.

To quantify possible edge effects, we undertake a sensitivity study examining changes in all meteorological inputs to FSCBG: temperature, relative humidity, wind speed, wind direction, and net radiation index.

Edge effects are an important factor in the determination of effectiveness of application. Effective swath width, the swath width for which 100% insect mortality rate is achieved, is defined as one value across the entire grid (Taylor et al., 1972). In Part 2 the effective swath widths predicted by FSCBG were shown to correlate well with effective swaths determined from field test data. However, for those trials in which pockets of lower deposition (caused by edge effects) were noted, the insect mortality rate in specific areas of the grid was not adequately represented by the effective swath width.

This report examines the possible causes of deposition edge effects by evaluating the sensitivity of a baseline deposition pattern to changes in meteorological conditions over the grid. The magnitude of local meteorological changes over short periods of time will be seen in the data recovered during the 1993 Utah Gypsy Moth Eradication Program (Teske, 1995). This data presents a detailed set of meteorological measurements for the time period from 3:00 AM to noon. Although the 1993 Gypsy Moth Program and the 1972 MISS test were not conducted over similar terrain and location, spraying took place at the same time of day (early to mid-morning) and at the same time of year. Therefore, meteorological data from the 1993 test are used to represent local meteorological variations that may existed been during the MISS test. The effect of these variations on the deposition contours of one of the MISS trials is then explored with a sensitivity study, and conclusions are drawn from the results.

2. MISS Field Trials Summary

The MISS test has been described in detail in Parts 1 and 2 of this study and is also documented in Taylor et al. (1972). It consisted of seven trials, six conducted at DPG, Utah and one in the Lolo National Forest, Montana. The trials were conducted from late April through late June 1972. Two spray systems were used: a FS system (used in trials FS1, 2 and 3) and the MISS system (used in trials FS4, 5, 6 and 7). The study described herein will address only one trial which was flown over the horizontal grid at DPG, using the FS spray system; all trials are summarized in Table 1.

The horizontal grid had 49 rows and 40 lines of horizontal sampling positions, all at ground level, spaced at 15.2 meter intervals. The portions of the grid used in each trial varied. In trials FS1, FS2, FS3 and FS6, Printflex card samplers were placed at every other grid sampling position, for a total of 625 sampling stations over the grid. The distance between sampling stations was 30.4 meters. This dense sampling array provides a detailed representation of the deposition pattern over the grid; field test data from these four trials is examined in this study. Figure 1 shows the horizontal grid and the aircraft flight path for trial FS2; other trials are similar and give similar results.

We will use trial FS2 as the baseline for the sensitivity study in this report. This trial was conducted over a dense sampling array which included stations with live insect larvae; it was thus included in both previous parts of this study. Trial FS2 was conducted in a crosswind during meteorological conditions typical of the entire test. While complete meteorological data are not available for all of the MISS trials, all available data for this trial are presented in Taylor et al. (1972). In Part 2 of this study, trial FS2 showed very good correlation of FSCBG predicted deposition with field test data (correlation to mass, R^2=0.72; predicted mortality rate within 10 % of observed mortality rate). Figure 2 shows an FSCBG simulation of this trial.

Meteorological measurements during the MISS test were taken with a 48-meter profile mast located in the vicinity of the target array (Taylor et al. 1972) and four 2-meter masts located at the corners of the grid array. The 48-meter mast was instrumented to measure: wind speed at 0.5, 1, 2, 4, 8, 16, 30, and 45.7 meters above ground; wind direction at 2, 16, 32, and 48 meters above ground; temperature at 1 meter above ground; and temperature gradient between 0.5 meter and 1, 2, 4, 8, 16 and 32 meters above ground level. The 2-meter masts measured wind speed and direction (these four masts are indicated on Figure 1).

Surface observations of dry and wet bulb temperature and cloud cover were taken 1500 meters northeast of the grid center, and pilot balloon (PIBAL) observations were taken at the same location (Taylor et al. 1972). In trial FS2, a C-47 cargo aircraft (the military version of the DC-3) was equipped with a FS spray system. Spray material was released at the rate of 150 gal/min for 1 minute, starting 805 meters upwind of the grid. Table 2 summarizes the meteorological data and spray system variables available for trial FS2, and Table 3 summarizes the aircraft characteristics of the C-47. The spray material is described in detail by Taylor et al. (1972). An estimate of the drop size distribution is shown in Table 4.

As previously described in Parts 1 and 2, following each trial the Printflex card samplers were collected, held until droplet stabilization (Taylor et al. 1972), then read. Visual observation and the Automatic Spot Counting and Sizing System (ASCAS, Young, Luebbe and Barry 1977) were used to recover the droplet spectrum of the ground level deposition pattern.

Ground deposition data generated for the trials consist of predominant drop size (drop diameter, in micrometers) and deposition density (in mg/sq m). Contours of ground deposition in trial FS2 are shown in Figure 3. Note that the edges of the contours are uneven. An FSCBG simulation of this trial of necessity predicts the average deposition for average meteorological conditions over the entire spray time (Figure 2). It is the meteorological influence on the ground deposition - producing unevenness in the deposition profile - that is the focus of this report.

Table 1: Scope of the 1972 MISS Test

Test Phase	Spray System	Trial No.	Location	Date of Trial	Release Ht (m)	Purpose
A	FS	FS1 FS2 FS3	DPG	27 April 27 April 27 April	150 - 300	Establishment of a baseline with the FS system compatible with Zectran® spray license criteria. Deposition density, area coverage, droplet spectra, liquid recovery and swath width evaluated. Petri dishes containing spruce budworm larvae were placed at special sampling positions during Trial FS3 to evaluate Zectran® effectiveness.
B	MISS	FS4 FS5	DPG	24 June 24 June	150 - 300	Preliminary trials: deposition characteristics of the MISS system
C	MISS	FS6	DPG	25 June	150 - 300	Comparison with the baseline established in Test Phase A to demonstrate that the MISS system meets Zectran® license criteria
D	MISS	FS7	Lolo National Forest	29 June	145 - 150	Demonstration of the effectiveness of the MISS system to suppress spruce budworm larvae in an infested coniferous forest

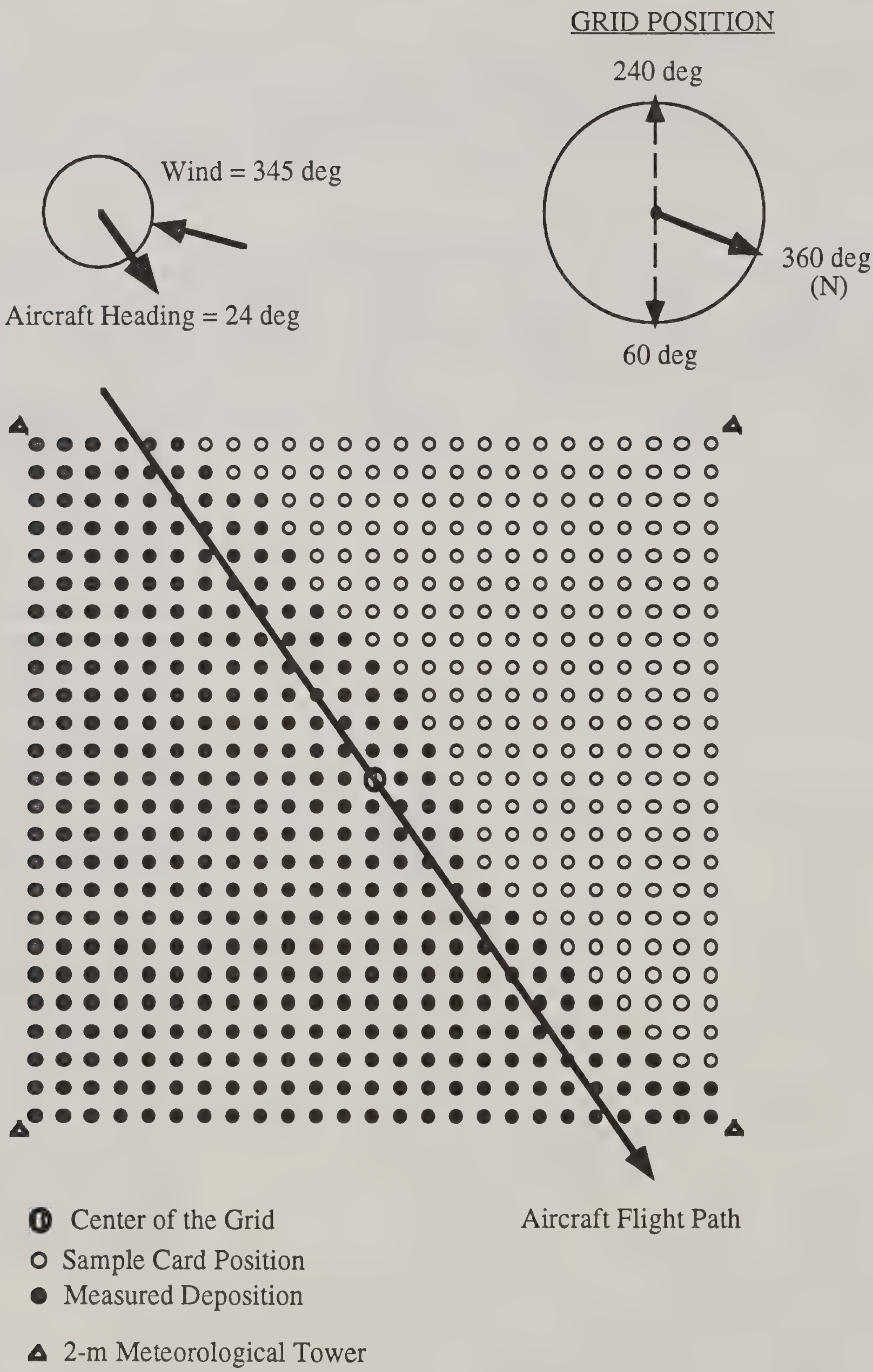

Figure 1: Trial FS2, horizontal grid at U.S. Army Dugway Proving Ground, Utah

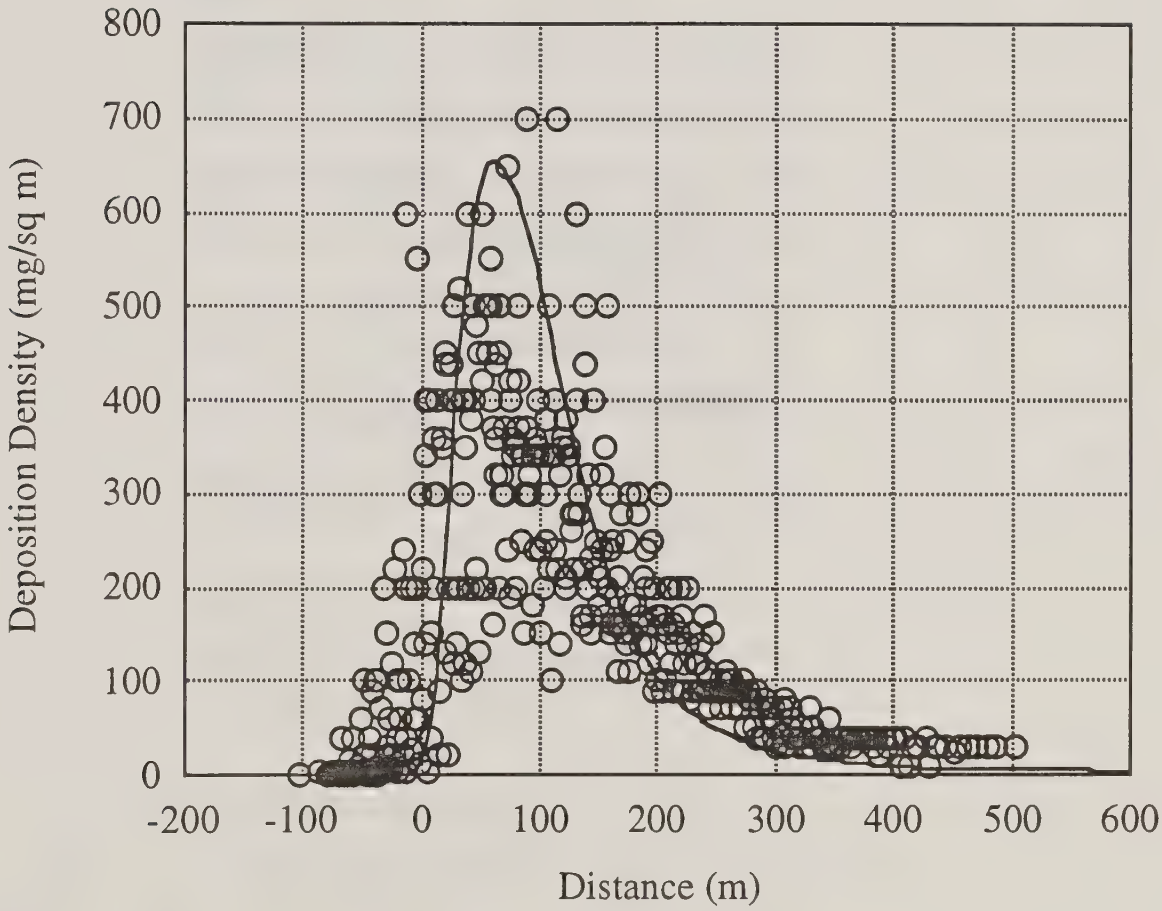

Figure 2: Observed and simulated ground deposition for trial FS2, at release height =61.9 m. Observed data are shown as open circles and simulated data are shown as solid lines.

Table 2: Summary of Meteorological Data and Spray System Variables for Trial FS2

	FS2
Time of Day (MST)	09:15
Relative Humidity (percent)	28
1-m Air Temperature (deg C)	11.06
Temperature Difference (0.5 to 32 m) (deg C)	-2.1
2-m Wind Speed (m/sec)	2.0
48-m Wind Speed (m/sec)	2.2
2-m Wind Direction (deg)	345
Aircraft Heading (deg)	24
Air Speed (m/sec)	65.8
Aircraft Height (m)	61.9

Table 3: Aircraft Characteristics for Trial FS2

Aircraft Type	C-47
Weight (kg)	9702.0
Wing Span (m)	28.82
Planform Area (sq m)	93.79
Drag Coefficient	0.1
Propeller Radius (m)	1.77
Propeller Efficiency	0.8
Blade RPM	2550.0
Number of Nozzles Assumed	46
Nozzle Type Assumed	8020
VMD Assumed (μm)	211.1
Flow Rate (gal/min)	150.0
Spraying Speed (m/sec)	66.82

Table 4: Drop Size Distribution Assumed for Trial FS2

Drop Diameter (micrometers)	Mass Fraction
45.88	0.0115
73.73	0.0274
106.35	0.0521
138.62	0.1180
171.03	0.1649
203.42	0.1674
235.88	0.1698
268.32	0.0843
301.32	0.0267
334.77	0.0435
366.72	0.0080
398.21	0.0145
430.71	0.0358
463.18	0.0422
495.68	0.0014
528.67	0.0325

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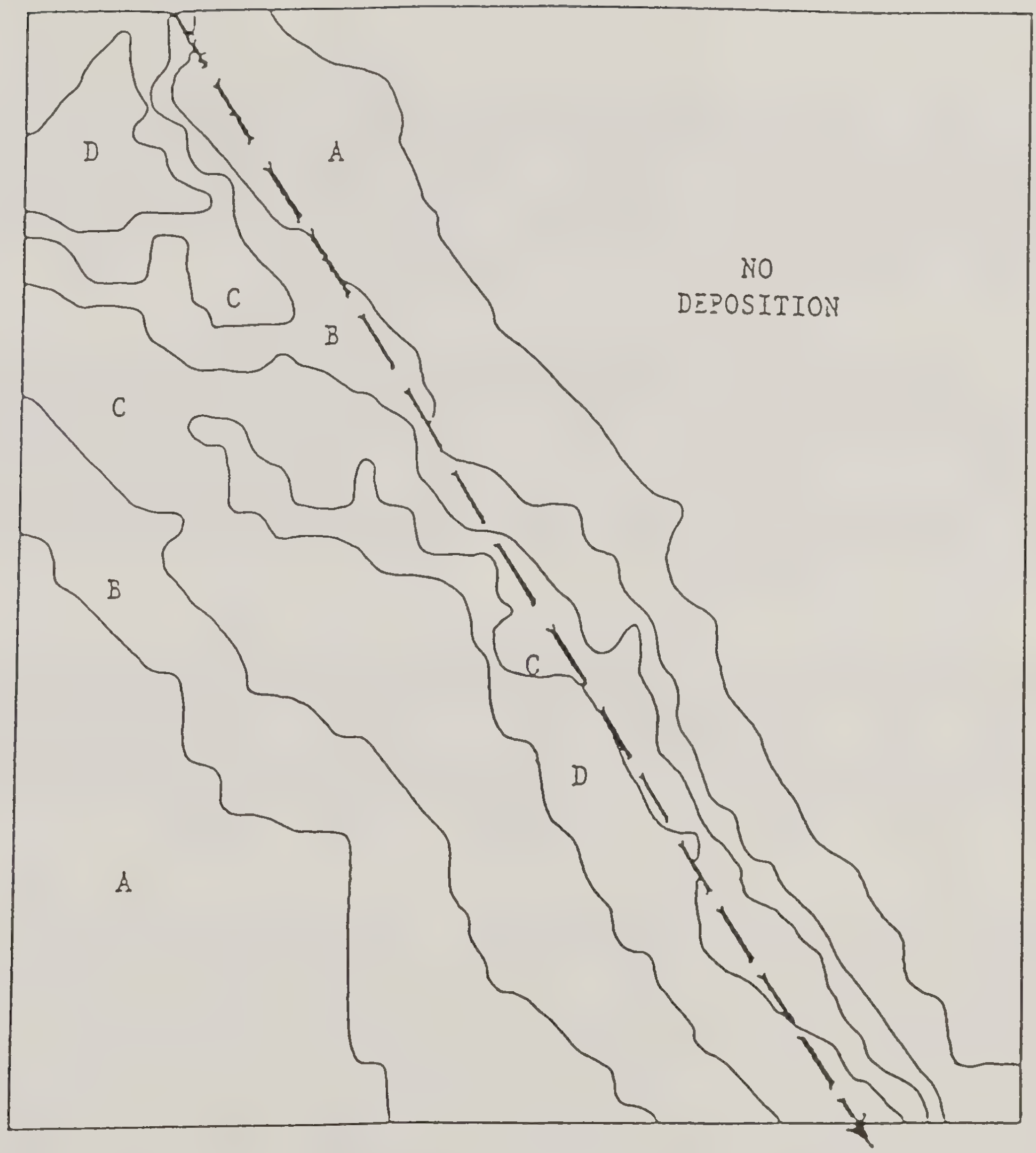


FLIGHT LINE

A 1 - 80 mg/sq m Deposition Density
B 90 - 170 mg/sq m " "
C 180 - 350 mg/sq m " "
D 360 - 700 mg/sq m " "

Figure 3: Trial FS2 deposition contour
(horizontal grid, U.S. Army Dugway Proving Ground)

3. EMCOT Meteorological Data Summary

For all the data collected during the MISS test, it could perhaps not be foreseen that detailed one-second meteorological data (temperature, relative humidity, wind speed and wind direction) would be needed 23 years later. Thus, to estimate edge effects due to time-dependent changes in meteorological conditions, we choose to use some current, accessible data to represent the MISS meteorological data in trial FS2. One such available dataset is the Utah 1993 data (Teske 1995).

The selected data were collected from three EMCOT towers (Ekblad, Windall and Thompson, 1990) positioned over several kilometers in Mill Creek Canyon, Salt Lake County. Data from each tower were recorded at one-second intervals from approximately 3:00 AM until noon for three days: May 28, June 4 and June 10, 1993. The sets of data are identified by tower number and day of testing. Figures 4 through 7 show wind speed, wind direction, temperature and relative humidity variations with time of day as measured at tower #3 on June 4.

The EMCOT data shown can not be used to simulate meteorological conditions at the time of the MISS test. However, the data can serve as a guide to the possible ranges of variation of meteorological variables for the sensitivity study. Each of the three days for which data were recorded at Mill Creek Canyon were deemed to be acceptable for spraying at the time of the test; thus, the data from tower #3 on June 4 can be used to represent meteorological variations during typical spraying conditions.

Table 5 shows the variation in meteorological conditions recorded at the three towers for all three days of EMCOT testing. As previously mentioned, data were recorded starting several hours before spraying and for several hours afterwards, in order to accurately present meteorological conditions until the sample cards were collected. For the purposes of this study, a time interval of interest was determined by evaluating net radiation data from each tower: from sunrise until 9:00 or 10:00 AM. Ranges of values over specified time intervals are shown for each parameter of interest: wind speed, wind direction, temperature and relative humidity. Table 5 also indicates the parameter ranges selected for the sensitivity study (discussed in section 4). The range of variability for each parameter in the study was chosen to bracket the EMCOT range.

It is apparent from Table 5 that there can be considerable variation in these parameters, particularly wind direction, over the course of a typical morning of spraying. Foe example, Figure 4 indicates that, from 6:00 AM to 10:00 AM on June 4, the wind speed at tower #3 varied from 0.6 m/sec to 3.8 m/sec and spiked sharply by as much as 1 m/sec in short periods of time. Figure 5 shows that, over the same period of time, wind direction at tower #3 varied from 40 degrees to 240 degrees, with rapid shifts of up to 180 degrees in time intervals of 5 to 10 minutes (just before 8:30 and again at 9:30).

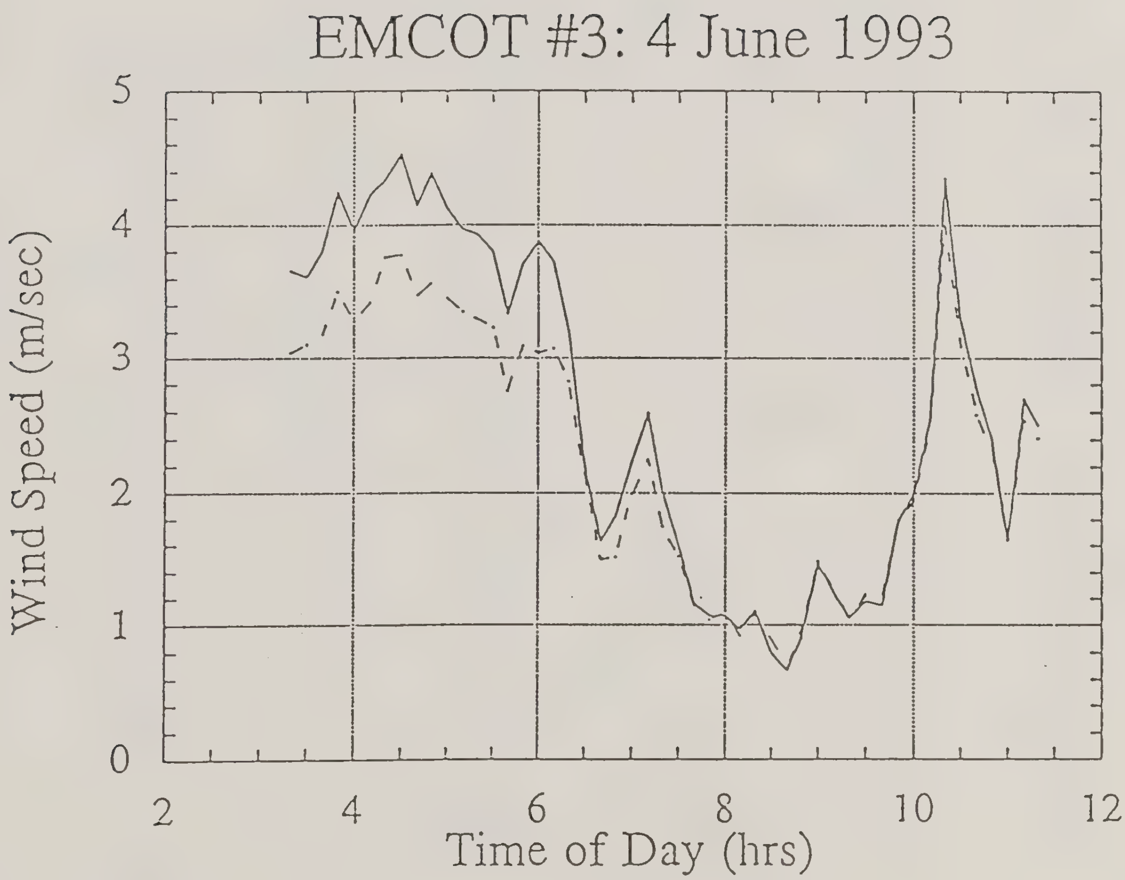


Figure 4: EMCOT #3: 4 June 1993, wind speed recorded at mid-height 3.5 m, dashed line) and at the upper height (6.1m, solid line).

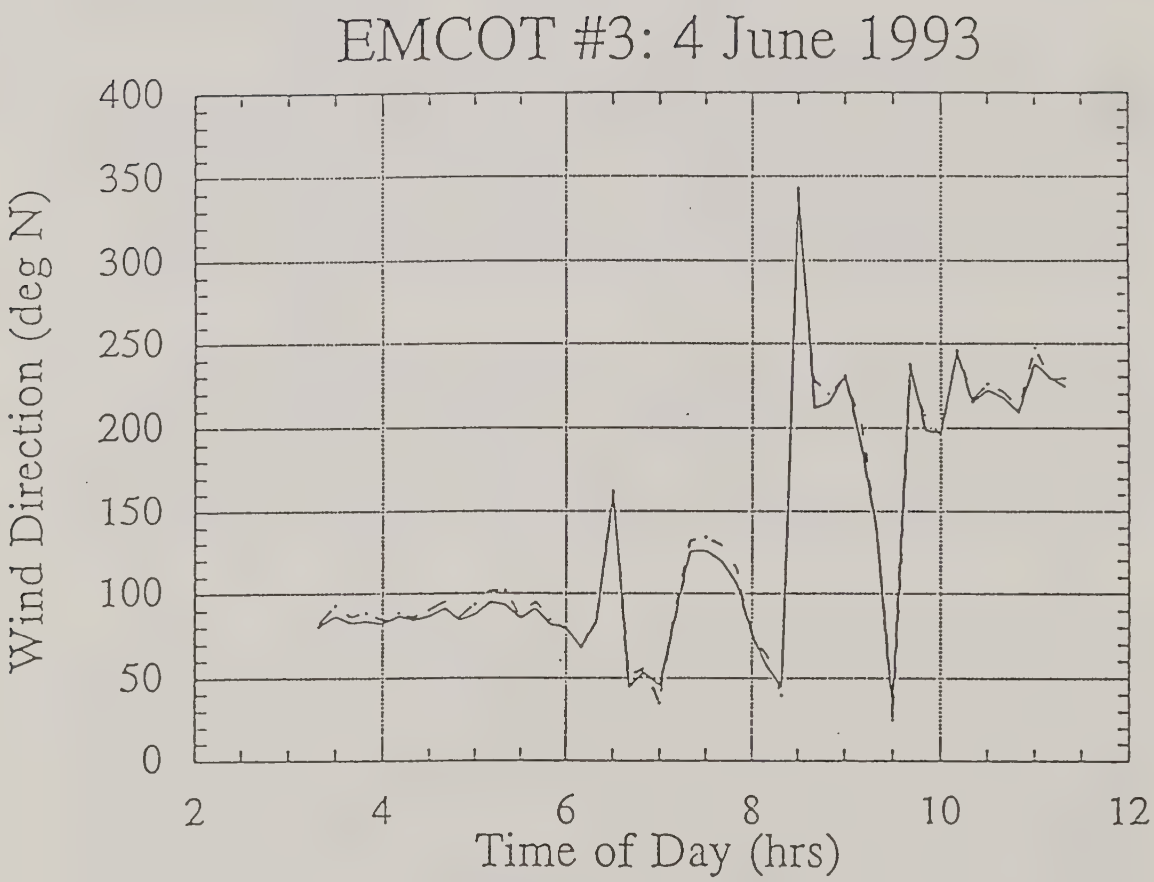


Figure 5: EMCOT #3: 4 June 1993, wind direction recorded at mid-height 3.5 m, dashed line) and at the upper height (6.1m, solid line).

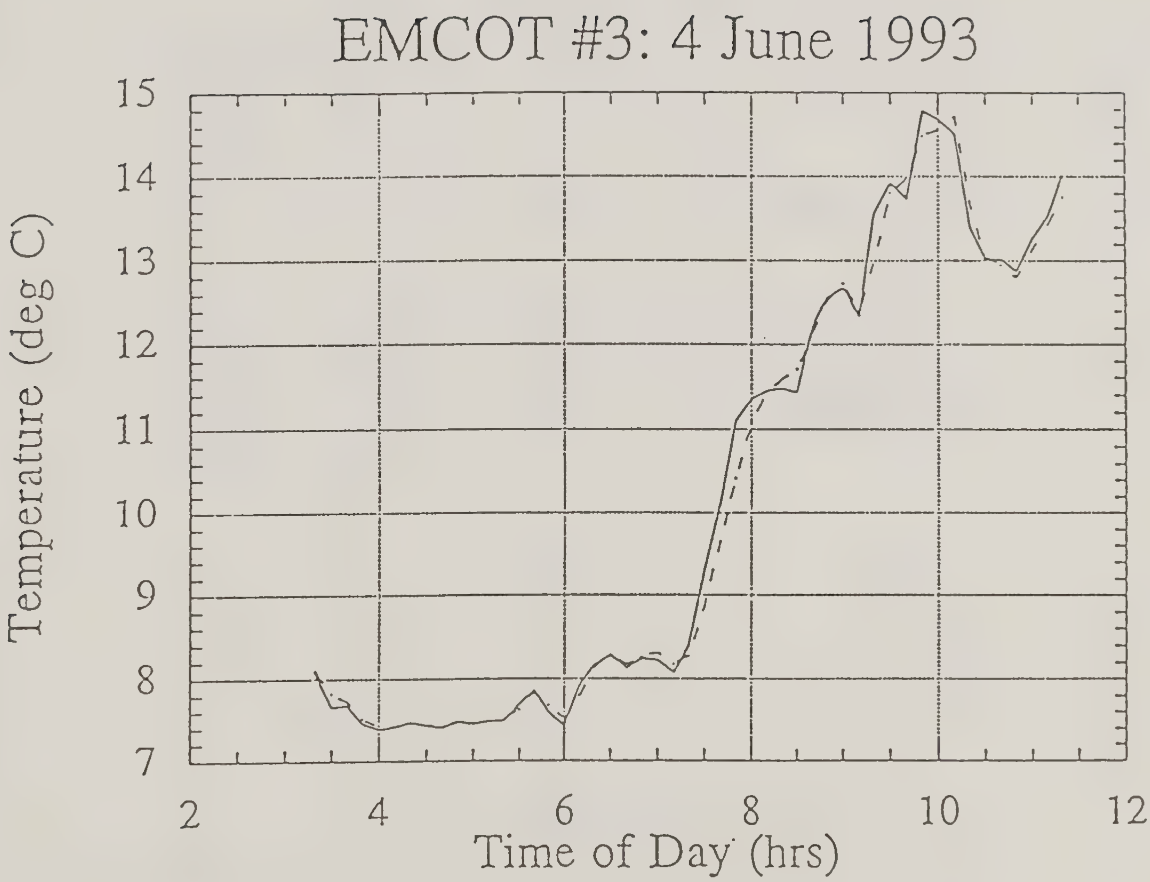


Figure 6: EMCOT #3: 4 June 1993, temperature recorded at the lower height 1.2 m, solid line) and at the upper height (6.1m, dashed line).

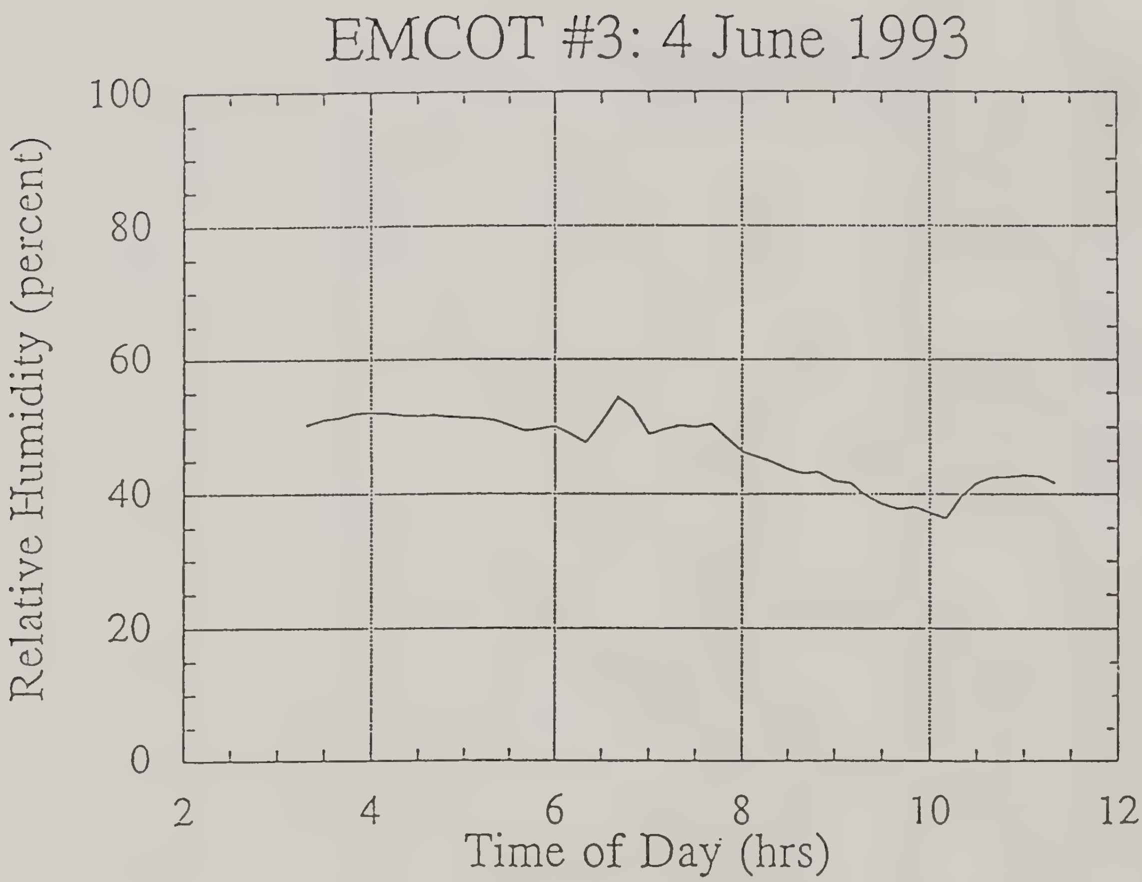


Figure 7: EMCOT #3: 4 June 1993, relative humidity recorded.

Table 5: Variation of EMCOT Meteorological Data Recorded During the 1993 Utah Gypsy Moth Eradication Program

Tower# and Date	Time Interval (hrs)	Wind Speed range (m/sec)	Wind Direction range (degrees from N)	Temperature range (degrees C)	Rel Humidity range (%)
28 May, 1993					
#1	8 to 10	0.3 to 1.2	150 to 325	10.5 to 19	60 to 30
#2	8 to 10	1.1 to 2.7	160 to 330	15.5 to 21.5	38 to 25
#3	7 to 10	1.1 to 2.5	70 to 280	15.5 to 21	42 to 30
June 4, 1993					
#1	7:30 to 9:30	0.3 to 0.7	150 to 310	3 to 11	87 to 45
#2	6 to 10	0.6 to 1.8	180 to 340	6 to 15	50 to 30
#3	6 to 10	0.6 to 3.8	40 to 240	7.5 to 14.7	50 to 36
June 10,1993					
#1	8 to 10	0.4 to 1.2	160 to 320	7 to 16	80 to 30
#2	8 to 10	0.7 to 1.4	150 to 310	13.5 to 17.5	43 to 25
#3	7 to 10	0.6 to 3.6	80 to 210	12 to 18	45 to 35
Study Baseline (trial FS2)	9:15	2.0	51	11.0	28
Parameter Ranges	NRI from -2 to 4	0.2 to 4.0	0 to 360	2.0 to 21.0	10 to 90

4. Study Guidelines

During the 1972 MISS test, spray was released for 1 minute as the aircraft flew over the grid at DPG. Meteorological measurements were taken on 2-meter masts at the corners of the grid and on a 48-meter mast in the vicinity of the test area. The test grid is 0.8 km x 0.8 km in size. Based on the EMCOT data shown in Figures 4 through 7, during even a short spray run, the meteorological data at a given point on the grid could be very different from the values recorded elsewhere on the grid. Furthermore, the data recorded at 2 meters might not adequately represent the actual meteorological conditions near the ground. Sample cards were not collected immediately after the spray run, but at some point in time afterwards when all of the deposited material had been captured.

Mathematical models such as FSCBG necessarily use average values of meteorological data to simulate conditions over the test area. Over the years these assumptions have been more than adequate to give good correlation of grid deposition predictions with field test data (MacNichol and Teske 1993a, 1993b, 1994a, 1994b). However, the meteorological data used to generate these predictions were averaged over the entire simulation, from the start of spraying until the collection of sample cards. Local variability in meteorological conditions can not be simulated by the Gaussian plume model in FSCBG.

In order to quantify the effect of local variability on the edges of a deposition contour, a sensitivity study has been performed using FSCBG to model changes in a baseline deposition profile which result from changes in the following parameters: wind speed, wind direction, temperature, and relative humidity.

Figure 8 shows the deposition profile for MISS trial FS2 at the baseline meteorological conditions given in Table 5. The edges of the predicted deposition are marked to correspond to the contour plot of field test deposition data developed in Taylor et al (1974), shown in Figure 3. The aircraft centerline is at 0 meters; all predicted deposition for the baseline is downwind of the centerline. Deposition level A is from 0 to 10 meters downwind of the aircraft centerline and from 225 meters downwind to the outer edge of the grid. Deposition level B is from 10 to 20 meters downwind of the aircraft centerline and from 175 to 225 meters downwind. Level C is from 20 to 40 meters downwind of the aircraft centerline and from 135 to 175 meters downwind, and level D is from 40 to 135 meters downwind of the aircraft centerline.

Figure 9 shows the contour plot previously presented, with uniform edges corresponding to Figure 8 superimposed on the original (field test) contour lines. The shaded area and underlined letters represent edges predicted by FSCBG. The field test contour edges can be seen to fluctuate considerably over the grid. The maximum amount of edge fluctuation occurs as the aircraft enters the grid, suggesting variation in meteorology, aircraft wake influences, or spray application. As the aircraft approaches the center of the grid (the shaded area), the edges fluctuate less, and each level of deposition is contained in a clearly defined band.

In order to evaluate shifts in the edges of deposition due to changes in local meteorological conditions, meteorological data in FSCBG were varied by one parameter at a time to generate new predictions of deposition. Predicted profiles over the entire range of a parameter were then compared to see how far away from the aircraft flight line specific levels of deposition occur. These shifts in levels of deposition correspond to shifts in the edge of the baseline deposition profile, and thus the predicted deposition contour.

Each meteorological parameter was only defined at one height. Wind speed and direction were defined at the upper EMCOT sensor height of 6.1 meters, and temperature was defined at the mid-height sensor position, 3.5 meters. Relative humidity was defined as a layered average value.

Net Radiation Index (NRI) was determined for the baseline model assuming minimal or partial high cloud cover at approximately 9:00 AM, to correspond to conditions at the time of MISS trial FS2. To bracket the possible variation in NRI during the EMCOT time period, the sensitivity study examined a range from -2 (before sunrise) to 4 (solar altitude at 90 degrees).

Variation in aircraft wake influences and spray application were not explored, since, as described in the next section of this report, meteorological changes could easily explain edge effects.

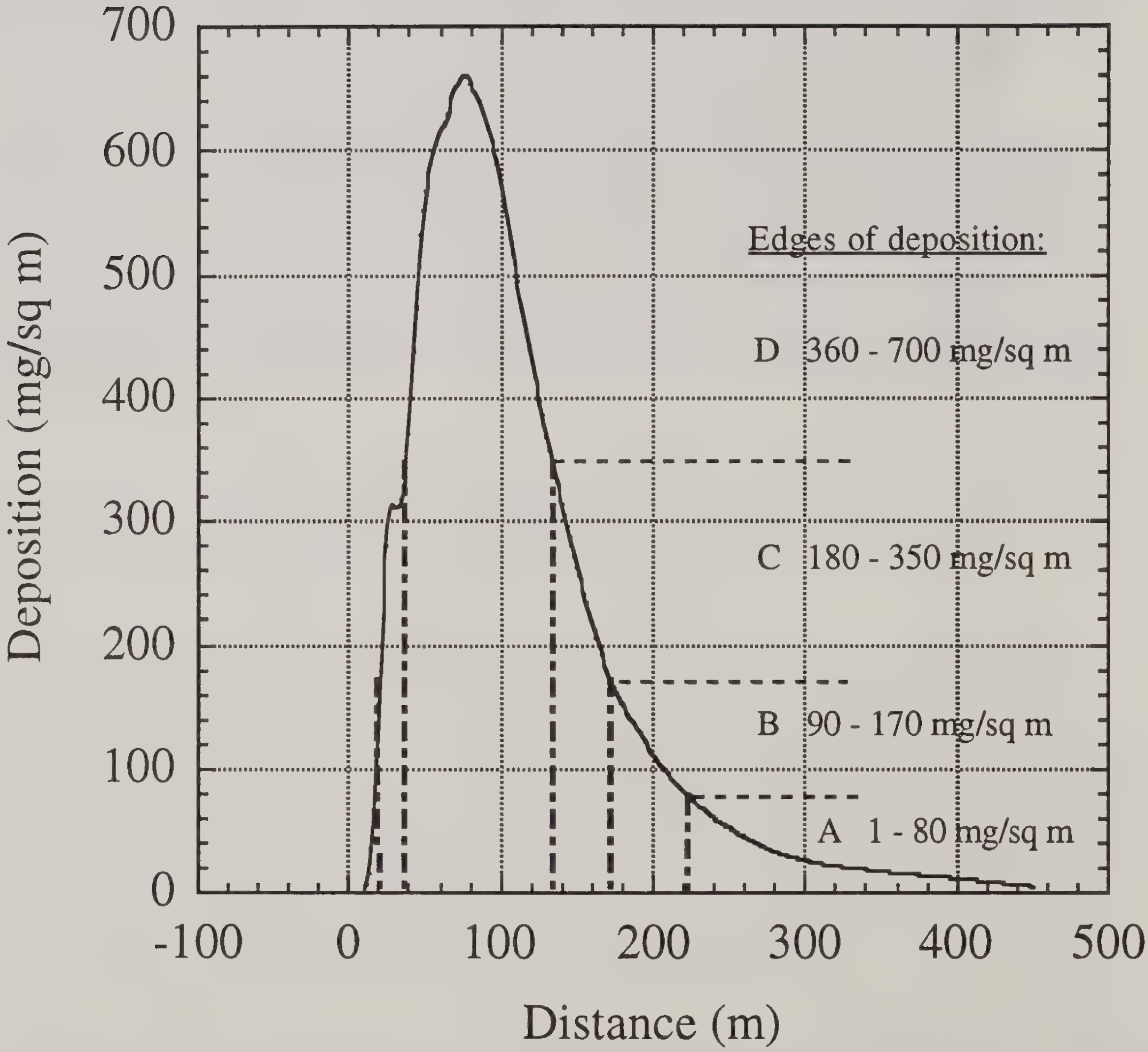


Figure 8: Baseline deposition profile (MISS trial FS2 at baseline conditions). The aircraft is flying at a distance of 0 meters, with a crosswind from left to right.

FLIGHT LINE

A 1 - 80 mg/sq m Deposition Density
B 90 - 170 mg/sq m " "
C 180 - 350 mg/sq m " "
D 360 - 700 mg/sq m " "

The shaded area shows uniform edges based on FSCBG predicted ground deposition (Figure 8). Tick marks are placed every 100 meters along a line perpendicular to the flight line.

Figure 9: Trial FS2 deposition contour (horizontal grid, U.S. Army Dugway Proving Ground), with FSCBG predicted deposition levels (shaded area).

5. Sensitivity of Deposition to Variation in Local Meteorology

Figures 10 through 14 show the predicted change in edge location due to changes in wind speed, wind direction, temperature, relative humidity, and Net Radiation Index (NRI), respectively. The figures show the predicted edge positions (in meters) for the range of parameter variability defined in Table 5, for levels of ground deposition corresponding to the contour edges of trial FS2: 1, 90, 180 and 360 mg/sq m. For example, Figure 10 shows that, at a wind speed of 0.2 m/sec, 1 mg/sq m of deposition is seen at -25 meters (25 m upwind of the aircraft centerline). This is a shift of -33 meters from the baseline profile, for which 1 mg/sq m of deposition occurs at 8 meters downstream. Thus, the edge of deposition at a level of 1 mg/sq m would shift 33 meters in the upstream direction for a sudden change in wind speed from 2.0 m/sec to 0.2 m/sec.

Table 6 shows the FSCBG predicted shift in edge position due to each parameter shown in Figures 10 through 14, for the given levels of ground deposition. Shifts in edge position are given relative to the position of the baseline predicted ground deposition shown in Figures 2 and 8. This is the predicted deposition along a line perpendicular to the aircraft flight path. Positive edge shifts are in the downwind direction, negative edge shifts are in the upwind direction.

It is apparent from Table 6 that edge position is most sensitive to changes in wind direction and wind speed, and much less sensitive to changes in the other meteorological parameters studied. The greatest sensitivity is to wind direction, followed by wind speed, NRI, relative humidity and temperature. These results are consistent with Teske and Barry (1993), where sensitivity factors for specific model parameters in FSCBG are defined. Large shifts in the levels of deposition can occur at a given location due to variability in wind direction and speed. Figures 15 and 16 show the predicted deposition profiles which result from changes in wind speed and wind direction, respectively.

In order to relate the sensitivities shown in Figures 10 through 14 to the actual field test deposition contour edges, Figure 17a shows the field test deposition contour lines for the downwind band of area B and the corresponding predicted band from Figure 9. Deposition density at the upwind edge is 90 mg/sq m. The downwind edge separates areas B and C; deposition density at this edge is 180 mg/sq m. Figures 17b and 17c show the effect of a 20 degree shift in wind direction and a 1.8 m/sec shift in wind speed on the edges of the predicted deposition. Shifts of these magnitudes are well within the ranges of variability shown by the EMCOT data (Figures 4 through 7).

A 20 degree shift in wind direction (from 51 degrees to 31 degrees) would result in the dashed set of contour lines (edges) in Figure 17b. A 1.8 m/sec change in the wind speed (from 2.0 m/sec to 0.2 m/sec) would result in the dashed set of contour edges in Figure 17c. The EMCOT data shown previously indicate that, during actual testing, several meteorological variables can change at once, and the changes are not uniform over the test grid. Note that the shifted edges in Figures 17b and c are each close to portions of the field test contour edges; by varying meteorological conditions locally, the predicted edges could be made to match the field test contour very closely. This step, however, would be very time-consuming, and would not actually be possible with the

Gaussian model in FSCBG. Dynamic changes in meteorological conditions could be programmed into the Lagrangian model in FSCBG, but could only be exercised with sufficient and extensive meteorological field data. Even then, this field data would be measured only at the data towers. Local (perhaps even random) changes in wind speed and direction (due to, for instance, gusts) would not be measured across the deposition grid.

Each dashed set of contour edges shown in Figures 17b and c represents a range of edge positions for area B in the predicted deposition contour for trial FS2. The ranges defined above account only for possible shifts in wind direction and speed. Similar ranges of edge position can be defined for the predicted contour edges of areas A, C and D. Table 6 indicates that shifts in edge position due to wind speed and wind direction become much greater at levels of higher deposition; thus, the edges of areas C and D would be expected to fluctuate more with meteorological variability than the edges of areas A and B.

Defining an expected range for edge position depends entirely on the chosen degree of variability in individual meteorological parameters. Without detailed meteorological data from the actual test being evaluated, this range can not be interpreted statistically. However, it is clear that even minor variability in wind parameters results in significant edge fluctuation over the grid.

According to Figure 14, small changes in the edges of the deposition can even be expected to occur as the sun rises and net radiation increases, especially in areas of heavy deposition. A shift in NRI from 0 to 4 results in a 3 meter shift in the predicted edge position for a deposition level of 90 mg/sq m, and in a 12 meter shift for a deposition level of 360 mg/ sq m.

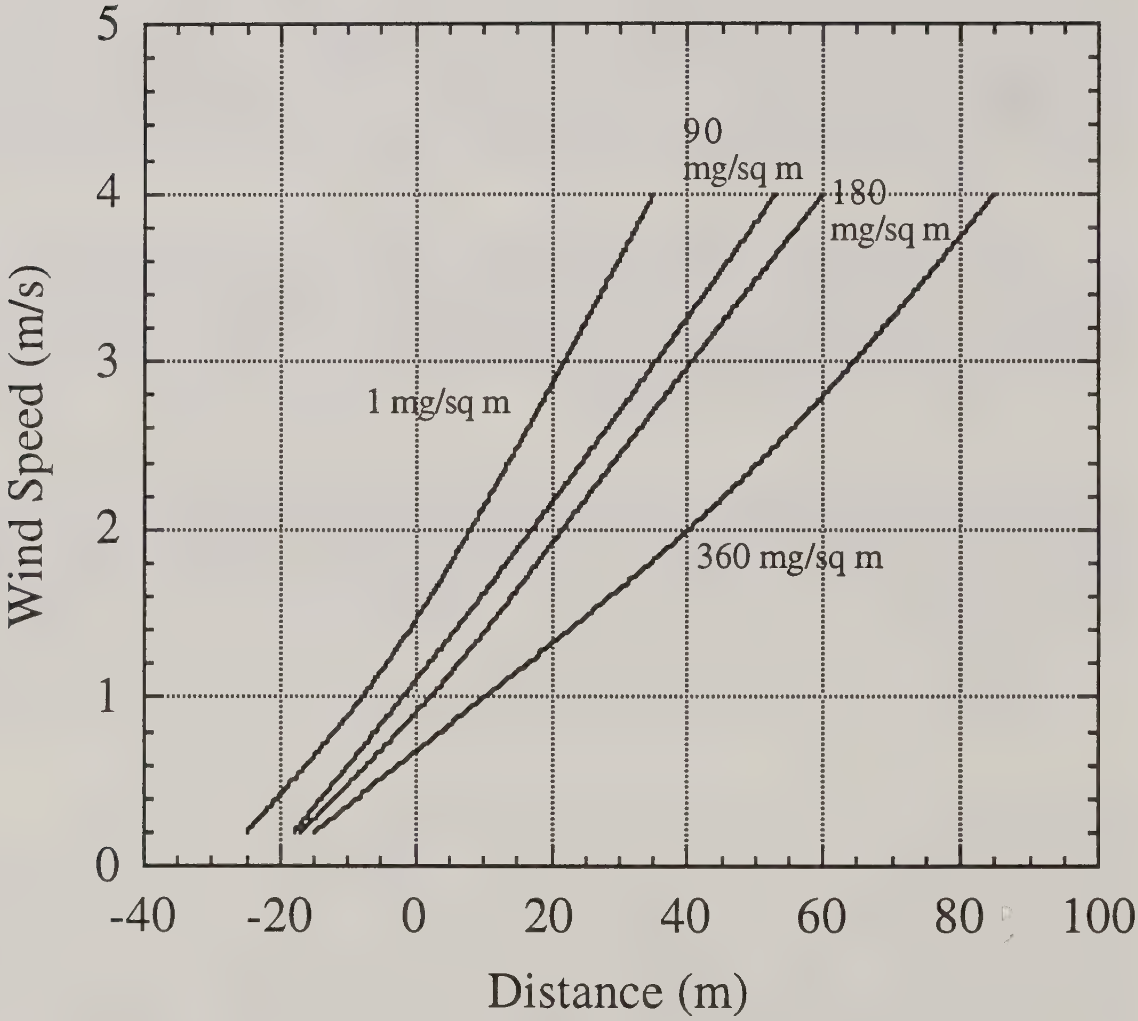


Figure 10: Edge sensitivity to wind speed. Baseline wind speed = 2.0 m/sec.

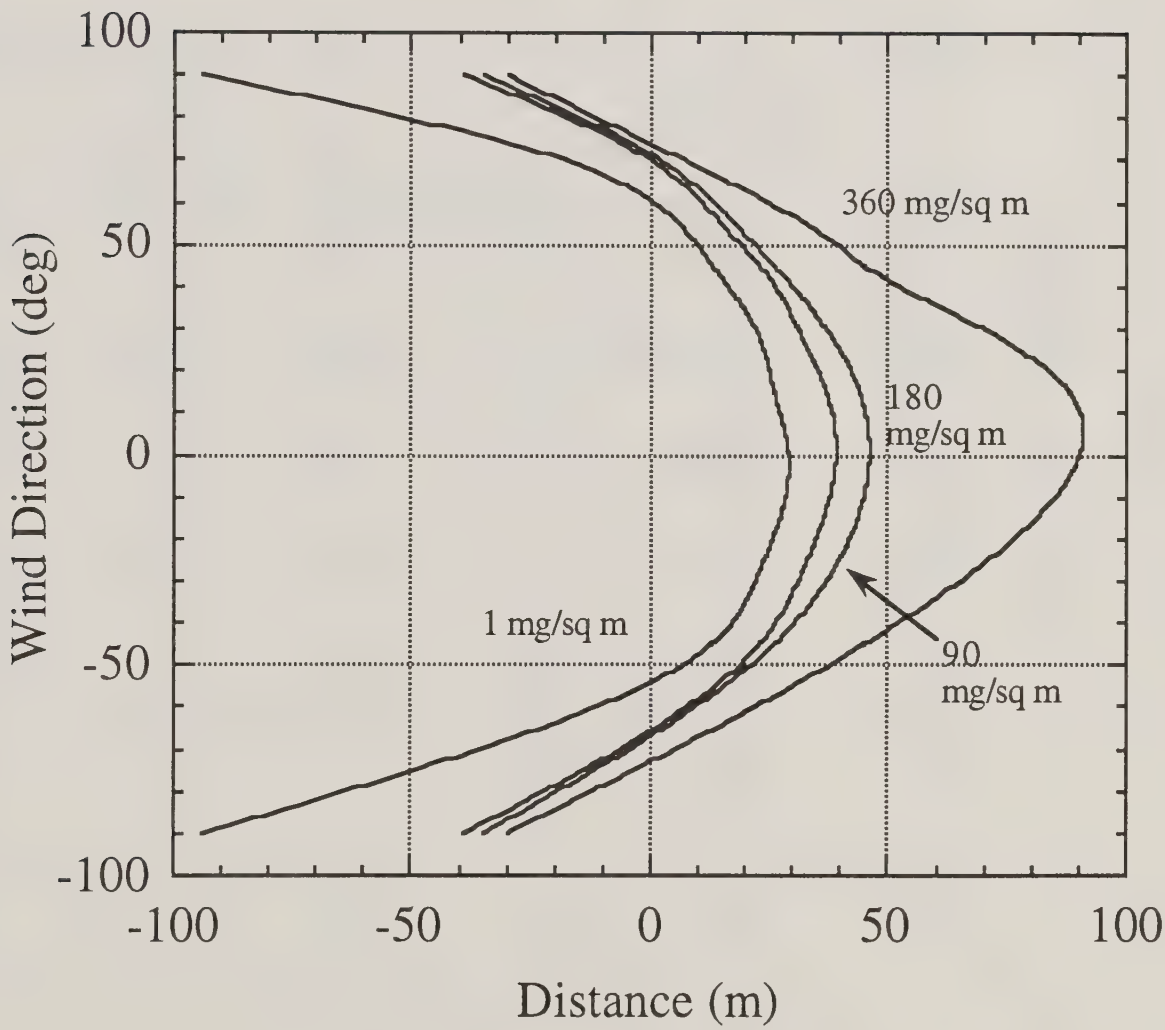


Figure 11: Edge sensitivity to wind direction. Baseline wind direction = 51 degrees.

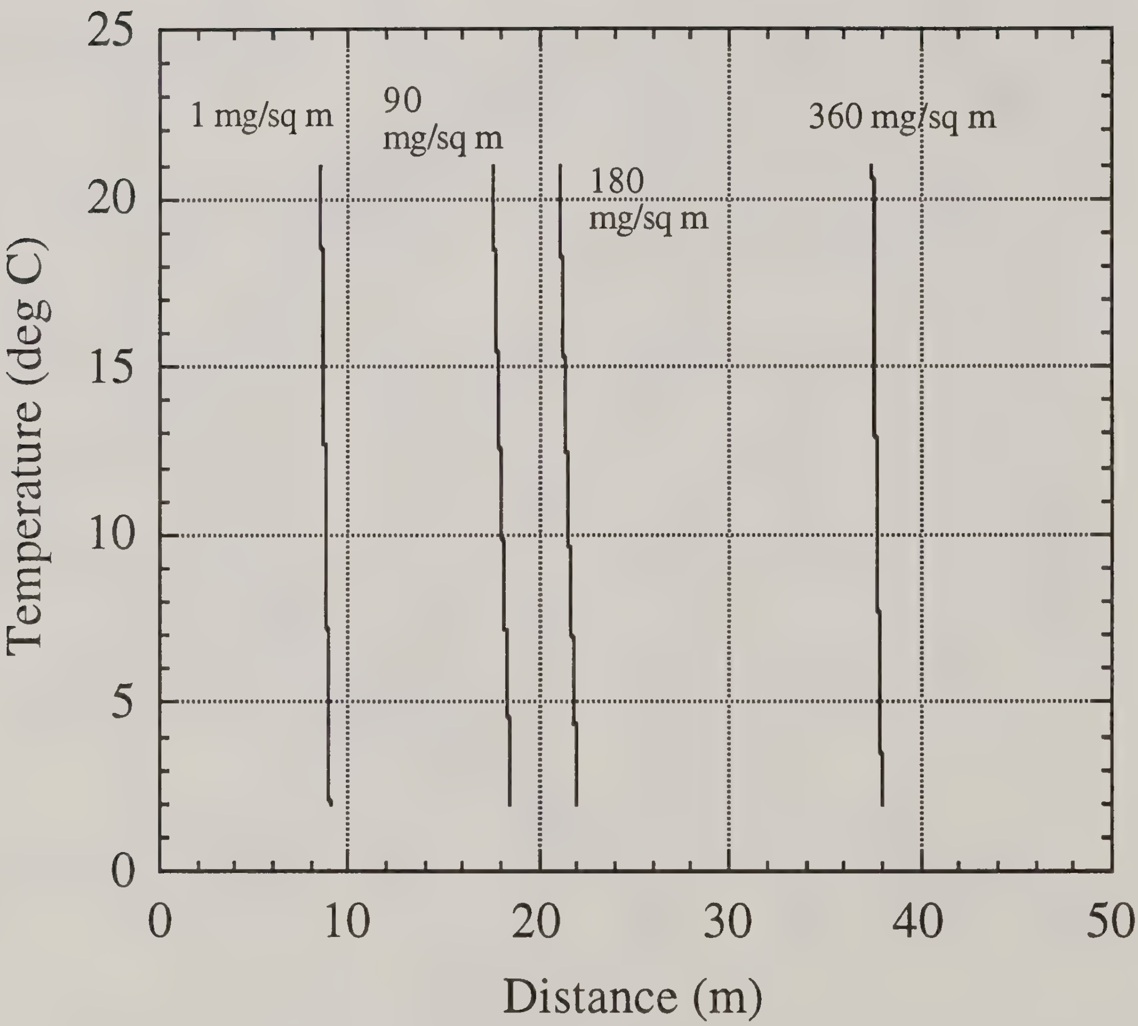


Figure 12: Edge sensitivity to temperature. Baseline temperature = 11 deg C.

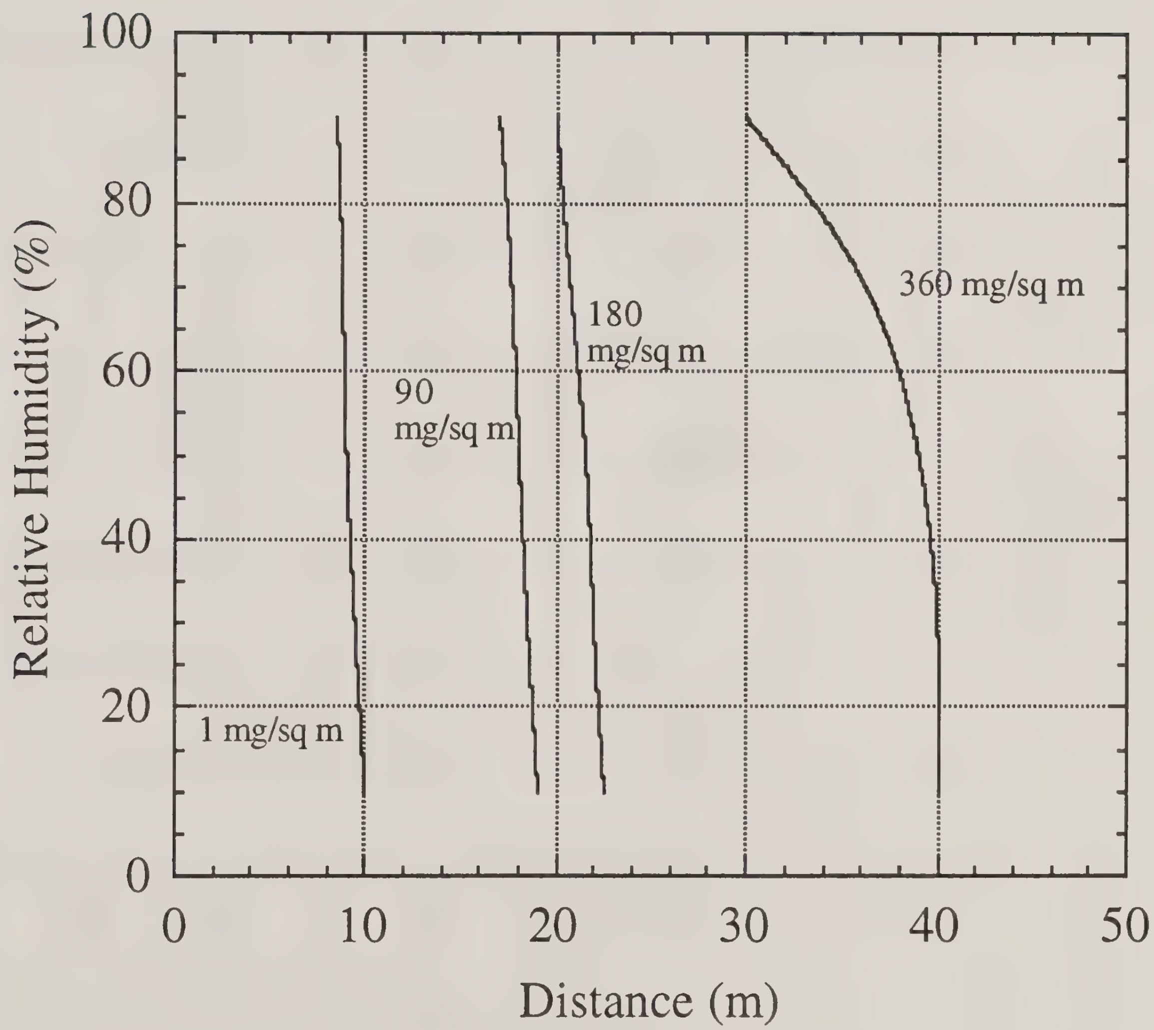


Figure 13: Edge sensitivity to relative humidity. Baseline RH = 28%

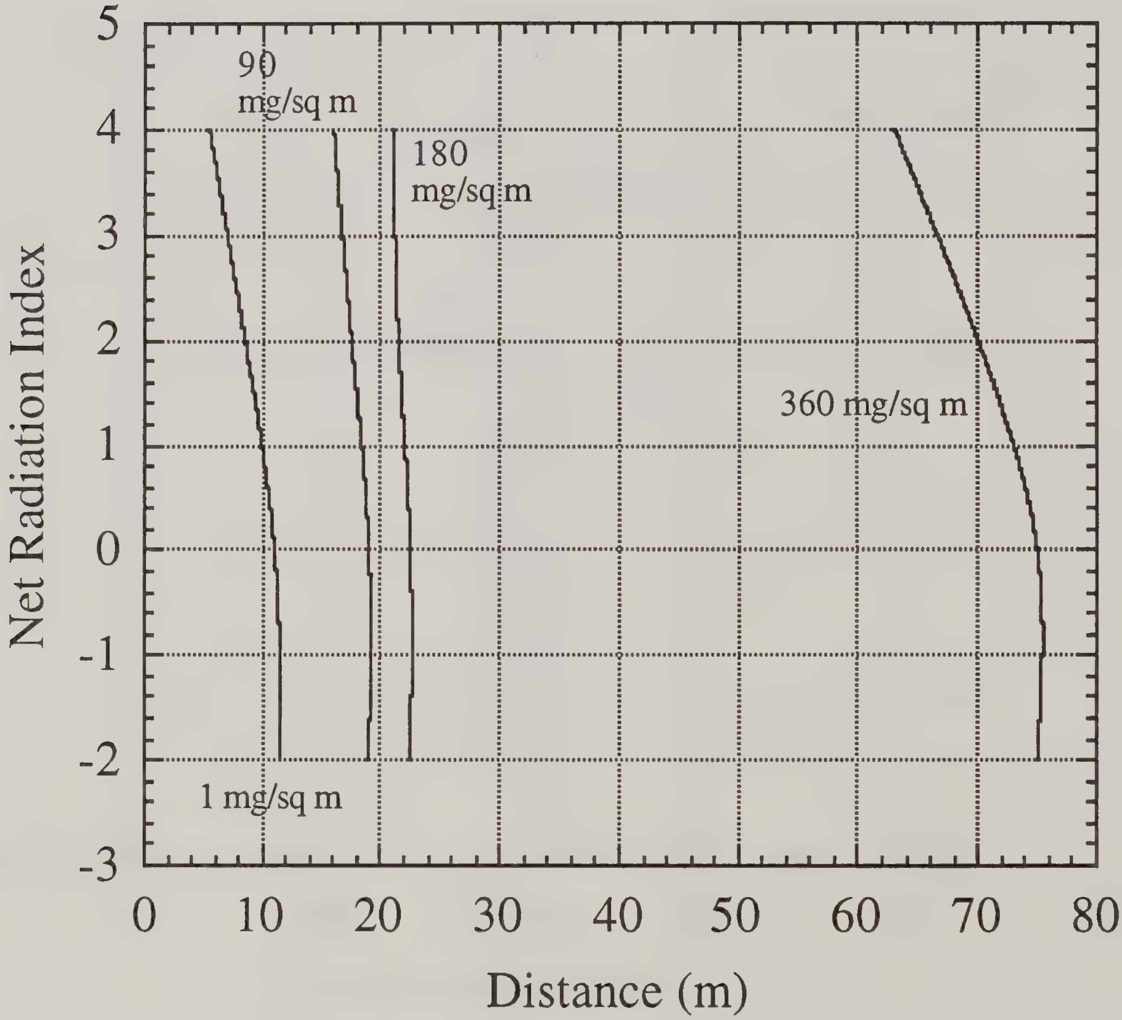


Figure 14: Edge sensitivity to Net Radiation Index (NRI). Baseline NRI = 2.0.

Table 6: Sensitivity of the Baseline Deposition to Changes in Meteorological Conditions

Meteorological Variable		Shift in Edge Position for Specific Deposition Level (meters change in distance from aircraft flight line)			
		1 mg/sq m Deposition	90 mg/sq m Deposition	180 mg/sq m Deposition	360 mg/sq m Deposition
Wind Speed:	0.2 m/sec	-33	-35	-36	-55
	1.0 m/sec	-16	-19	-24	-30
	2.0 m/sec *	---	---	---	---
	4.0 m/sec	27	36	39	45
Wind Direction:	0 deg	20	21	25	52
	15 deg	17	19	23	50
	30 deg	13	13	16	32
	45 deg	4	5	5	7
	51 deg *	---	---	---	---
	70 deg	-27	-18	-19	-31
	90 deg	-103	-57	-56	-68
	135 deg	-22	-41	-47	-52
Net Radiation Index:	-2	3.0	2.0	1.0	5.0
	0	2.5	1.5	1.0	5.0
	2 *	---	---	---	---
	4	-3.0	-1.5	-0.5	-7.0
Temperature:	2 deg C	0.5	0.5	0.5	0.5
	7 deg C	0.3	0.3	0.3	0.3
	11 deg C *	---	---	---	---
	21 deg C	-0.5	-0.5	-0.5	-0.5
Relative Humidity:	10%	0.5	0.5	0.5	0
	28% *	---	---	---	---
	50%	-0.5	-0.5	-0.5	-1.0
	90%	-1.0	-1.5	-2.0	-10.0

* denotes the baseline case

Positive shifts in edge position occur in the downwind direction.

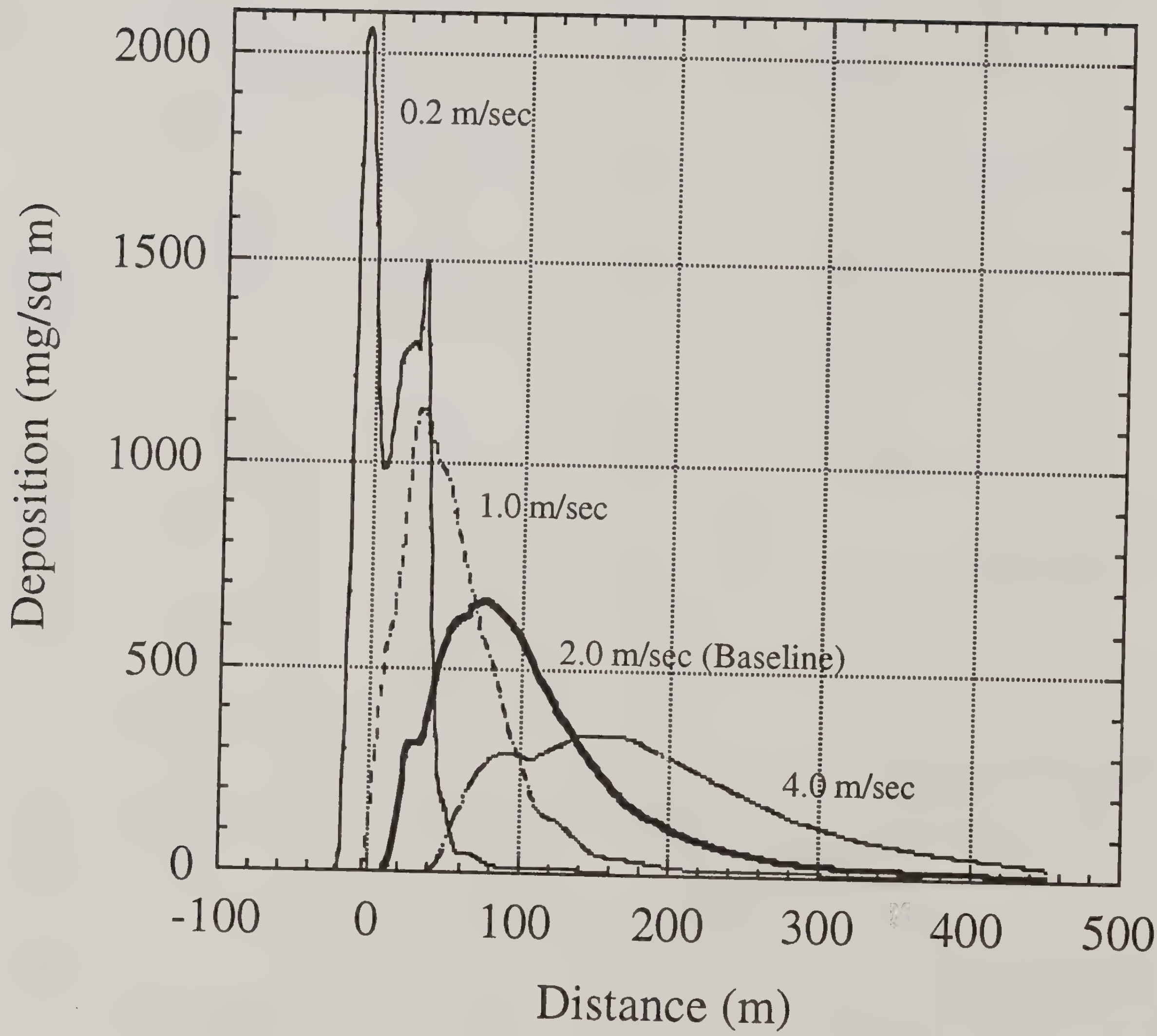


Figure 15: Sensitivity to changes in wind speed (baseline deposition, solid line).

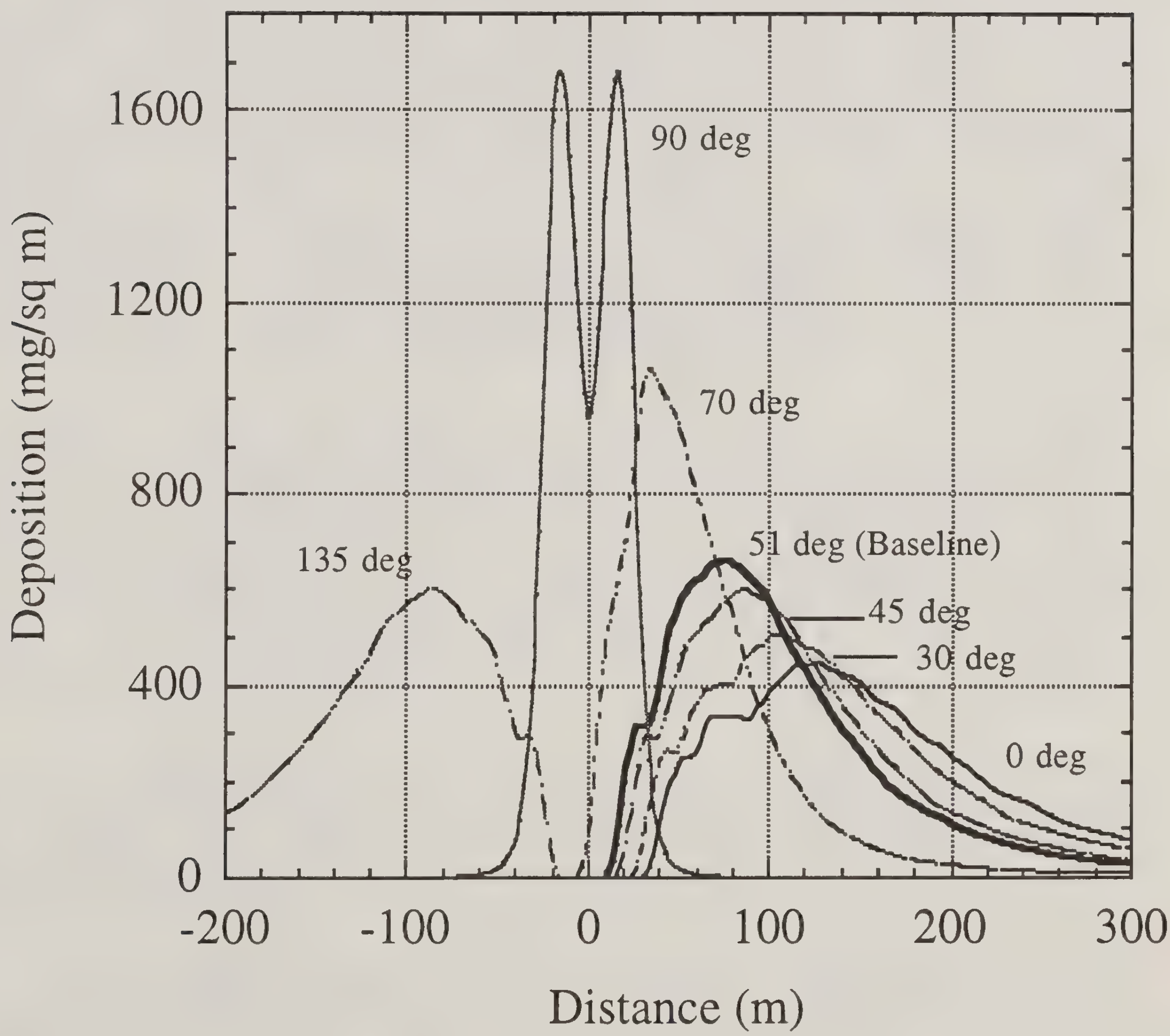


Figure 16: Sensitivity to changes in wind direction (baseline deposition, solid line); 90 degrees is in-wind.

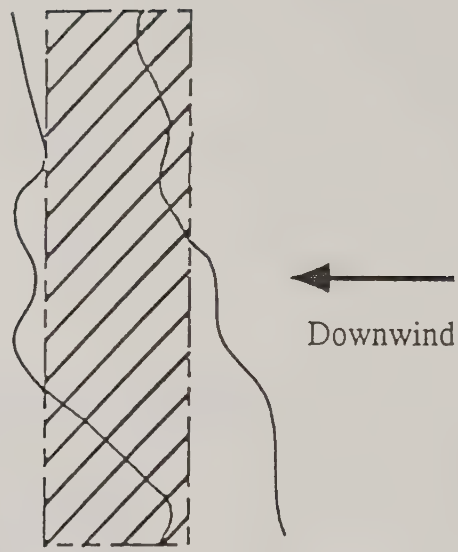
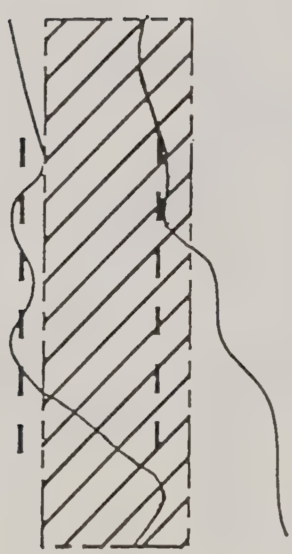


Figure 17a: Field test deposition band B
(90 -170 mg/sq m) and baseline predicted
band B (shaded).



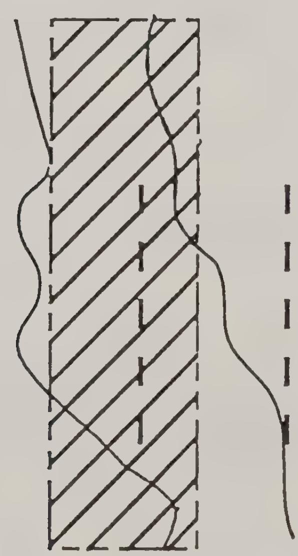


Figure 17b: Effect of a 20 degree shift in wind direction on predicted contour edges (new predicted edges are dashed).

Figure 17c: Effect of a 1.8 m/sec shift in wind speed on predicted contour edges (new predicted edges are dashed).

Figure 17: Sensitivity of MISS trial FS2 deposition contour to changes in wind speed and wind direction.

6. Conclusions and Observations

We have shown that deposition contour variation can be generated by varying the meteorological parameters in the FSCBG model of the field trial. Although the exact contour edge observed in field data can probably never be modeled due to localized meteorological variability, and possibly uncontrolled variation in spray application, an expected range of edge positions can be predicted if detailed (one-second) meteorological data over the test area are available.

It should be noted that this study examined meteorological variables, and did not address such model parameters as release height, spraying speed and drop characteristics of the spray, and variation in spray application. These parameters are shown by Teske and Barry (1993) to be very important to accurate simulation of field test data. A slight shift in release height over the grid, for example, would affect the edges of deposition at least as much as a slight shift in wind direction or speed at the same location. As was previously noted, the field test contour plot of trial FS2 shows a great degree of edge instability as the aircraft first enters the test grid, indicating possible variation in aircraft or spray parameters in addition to meteorological variability. From the minimal meteorological data available for the MISS trials, it is impossible to tell exactly what type of variability in test conditions is occurring at a given point on the grid.

In fact, while changes in aircraft and spray parameters (such as release height) are quantifiable, changes in local meteorology may occur suddenly and will occur at any height, even at ground level. Changes in the atmospheric boundary layer are constantly occurring as a result of such phenomena as the Coriolis effect. In the early morning hours, the wind can shift dramatically with altitude, particularly below 100 meters, resulting in significant wind shear (Lewellen, Teske and Donaldson, 1974). Such changes in field meteorology are often unpredictable and can be extremely difficult to measure (and even more difficult to model), yet they can have a significant effect on droplet deposition.

Meteorological concerns aside, the amount of variability seen in the field test deposition contour edges for trial FS2 occurs over relatively flat terrain. The presence of complex forest terrain, typical of most areas sprayed by the Forest Service, could only amplify the edge effects, and may suggest concerns about using a model to predict very complicated physical processes. We will speak to that presently.

Because of the many possible sources of variability in meteorological conditions and aircraft and spray parameters, deposition edge effects will be present in all field test data. As shown in the previous section, predicted deposition profiles will not account for these edge effects. It is possible to define shifts in the position in the predicted edges of deposition due to changes in specific meteorological parameters, but such shifts in edge position can not be modeled with any accuracy unless detailed meteorological data are available for the entire test area. Nevertheless, in Part 1 of this study (MacNichol, 1994), FSCBG predicted deposition over the densely sampled MISS test grid was shown to fall within an assigned measure of statistical confidence. In Part 2 (MacNichol and Teske, 1995), predicted deposition profiles showed good correlation to field test deposition data regardless of the presence of contour edge effects.

Thus, it is obvious that variations in deposition are expected during aerial application of spray materials. With sufficient meteorological data, we should be able to quantify the effect of these variations (this is the intent of the present Part 3 report). With sufficient ground deposition data, we should be able to quantify the further effects of all mission parameters, including aircraft effects (this was the intent of the Part 1 statistical report). Nonetheless, the use of a model such as FSCBG is seen to recover the **average** deposition profiles to be expected from the spray project (this was the intent of Part 2 of this study, and numerous other referenced data comparisons). The engineering is not available at this time (and may never be available) to quantify every transient atmospheric effect. Rather, the sum of the present extended study of the 1972 MISS trials is that FSCBG can be used not only to capture the mean of the measured deposition profile (Part 2), but also, with detailed meteorological data and multiple card lines, to suggest confidence intervals around the predicted deposition pattern (Part 1), and to quantify the effects of rapid changes in field test conditions on the resulting deposition pattern (Part 3).

6. Acknowledgment

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